Qubit-Photon Corner States and Other Ultrastrong Coupling Physics

Juan José García Ripoll (IFF-CSIC, Spain)

with many collaborators…

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Roadmap

Quantum microwave photonics

Strong and ultrastrong coupling

Theoretical tools

Polaron and MPS methods

Experimental tools

Measuring single photons in frequency and time

Photon corner states

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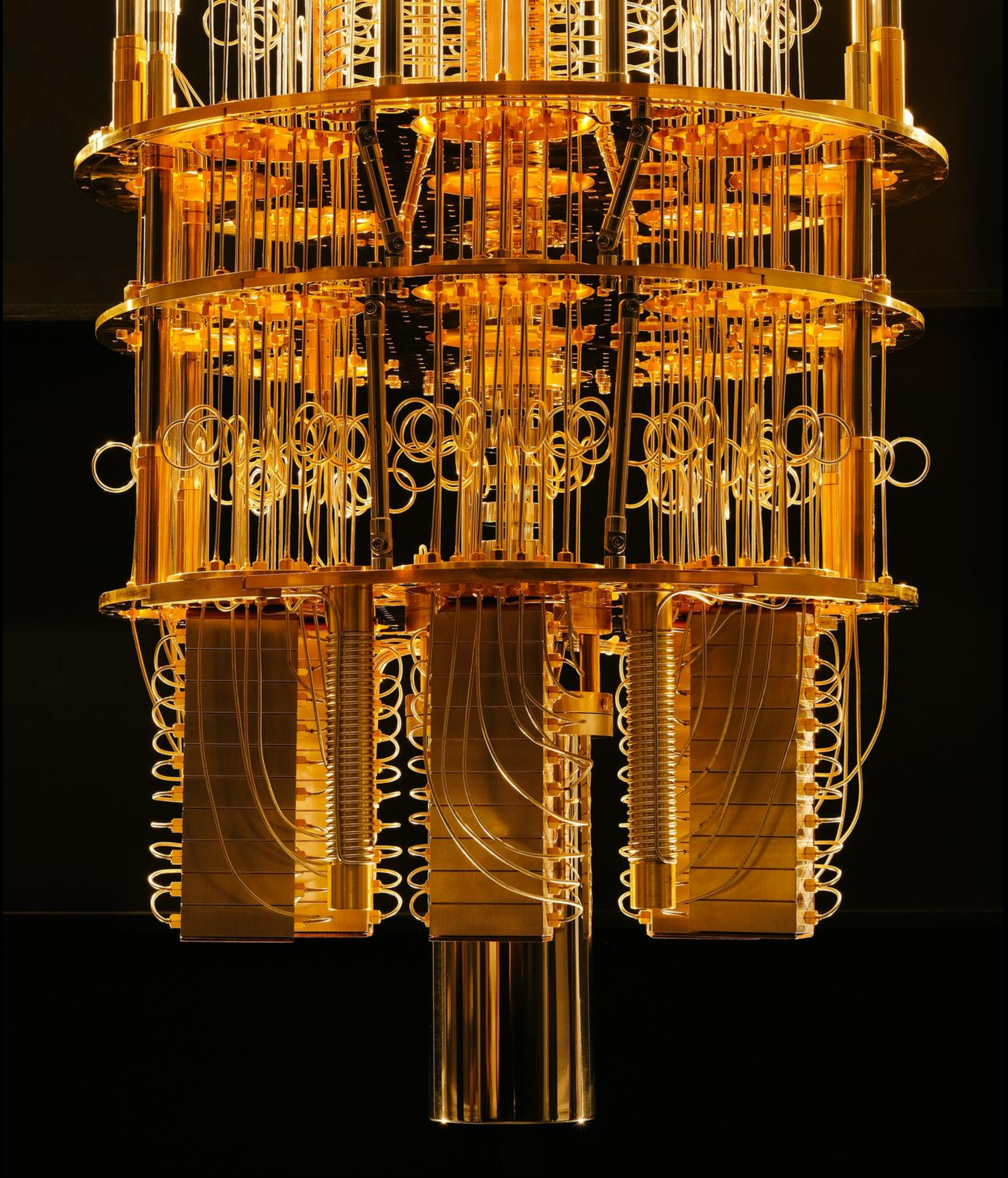
Photon corner states



Low temperature Physics

- Typical energy scales

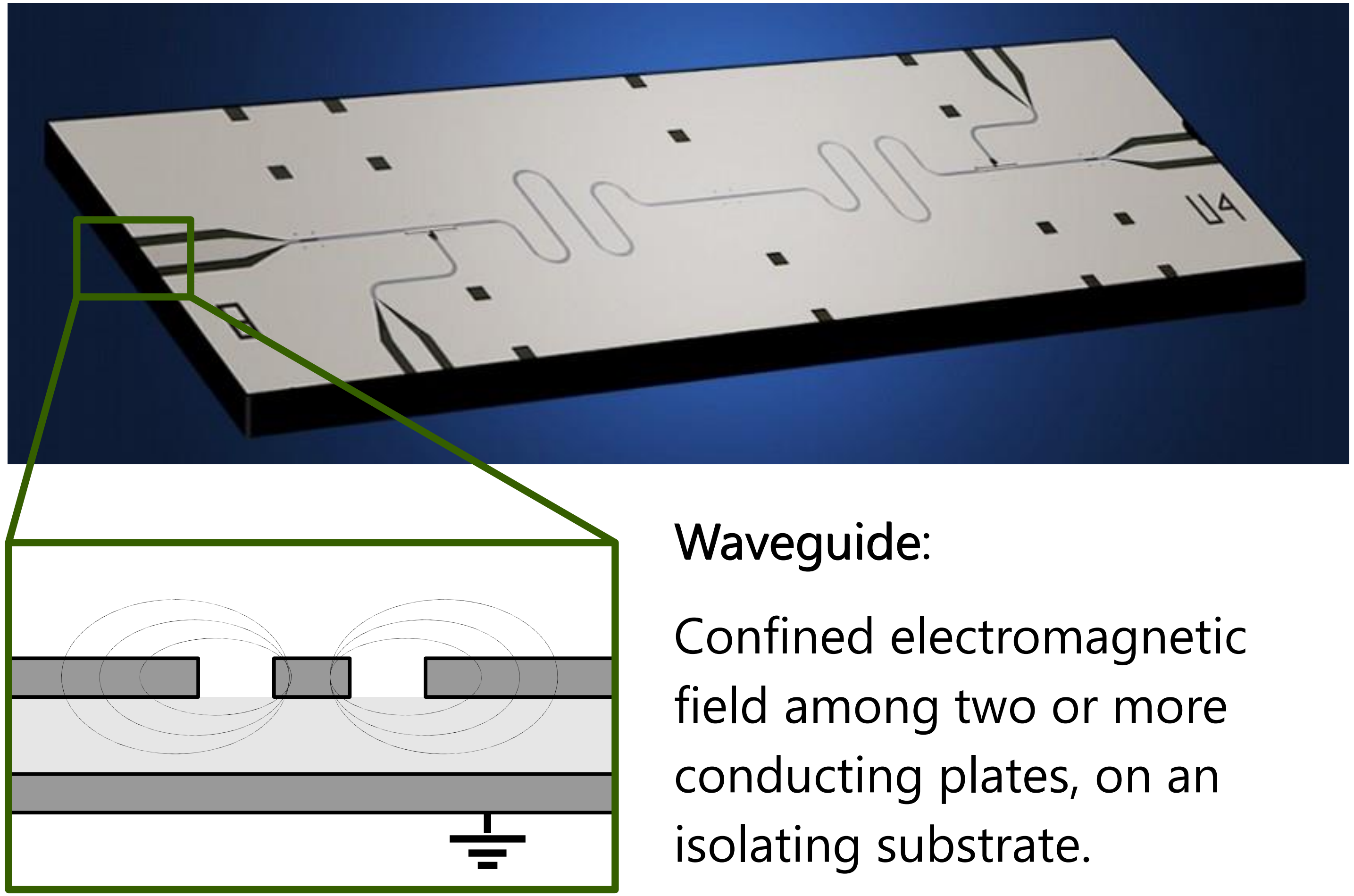
  Microwaves, 1- 30 GHz
- Associated temperatures

  T ~ 0.05 - 1.5 K
- Work in dilution refrigerators

  T ~ 11-20 mK
- Superconductors:

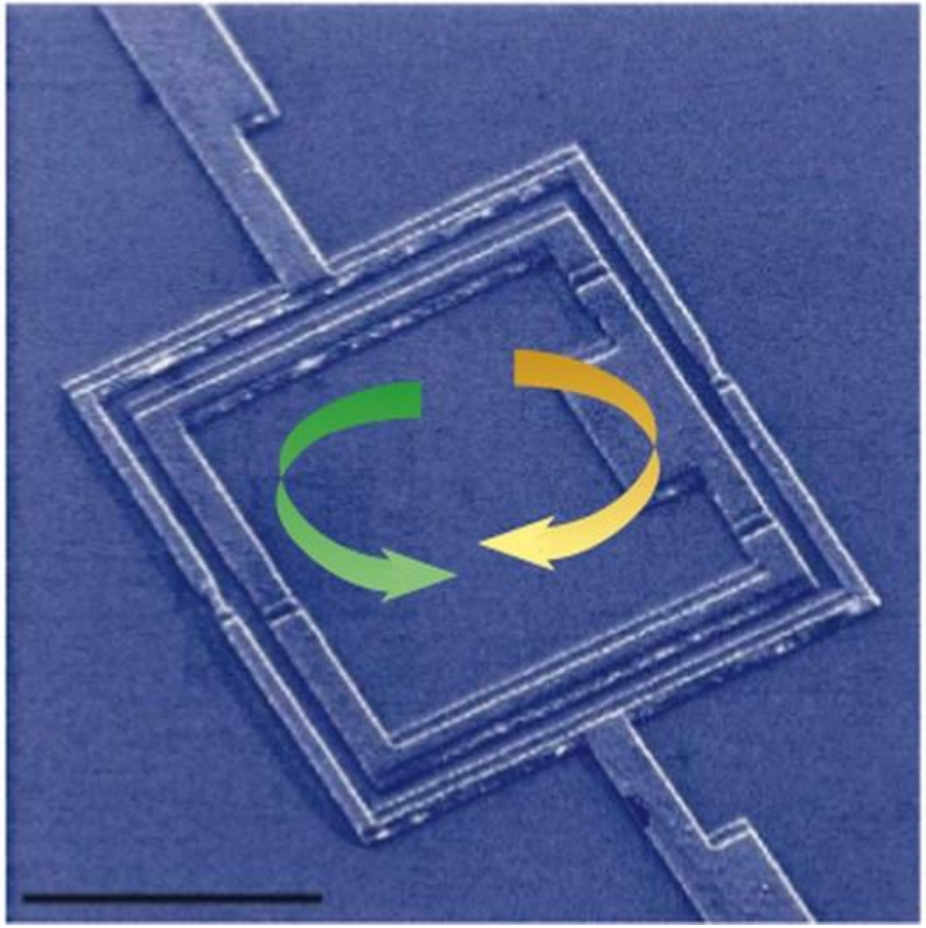
  Al, Nb, ...
- Size, heating? Interface to outer world? Amplification & detection? ...

Microwave light and artificial atoms

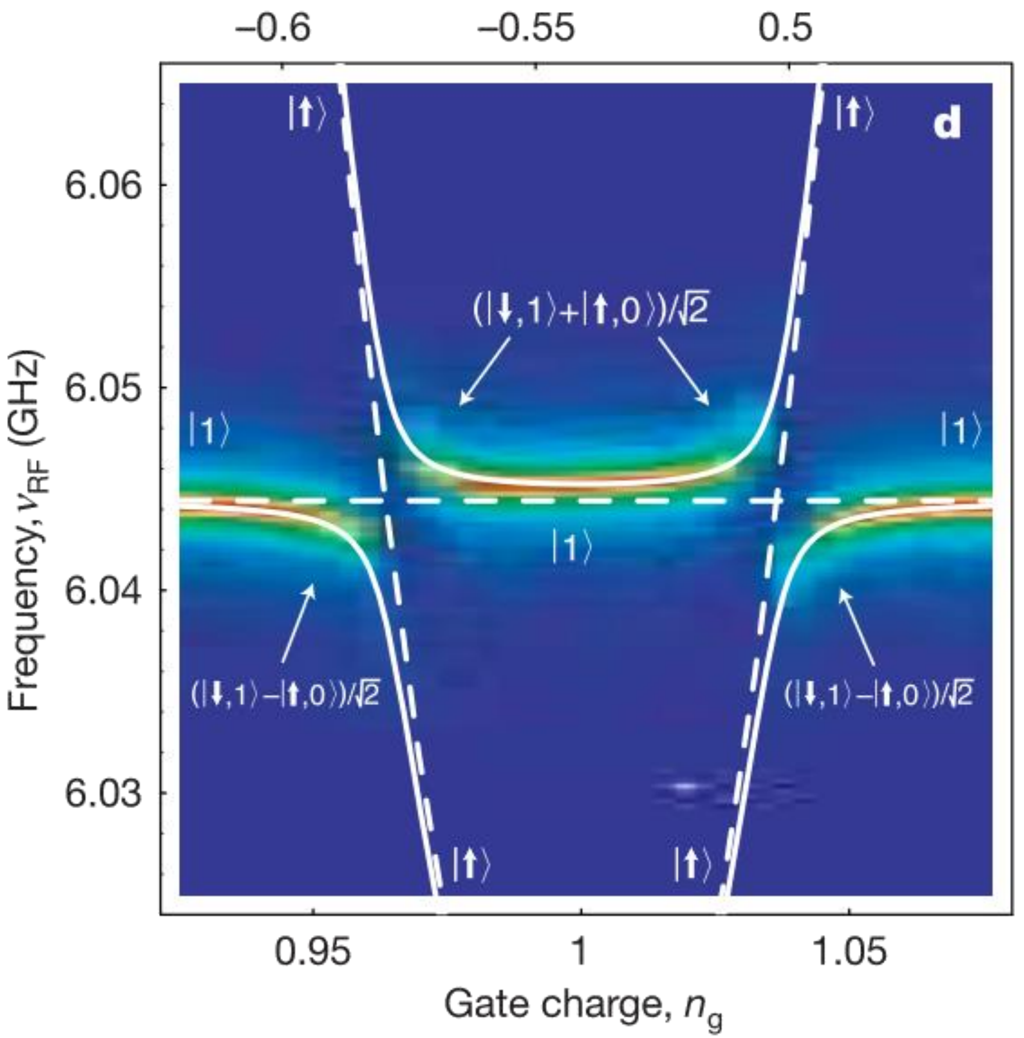


Waveguide:

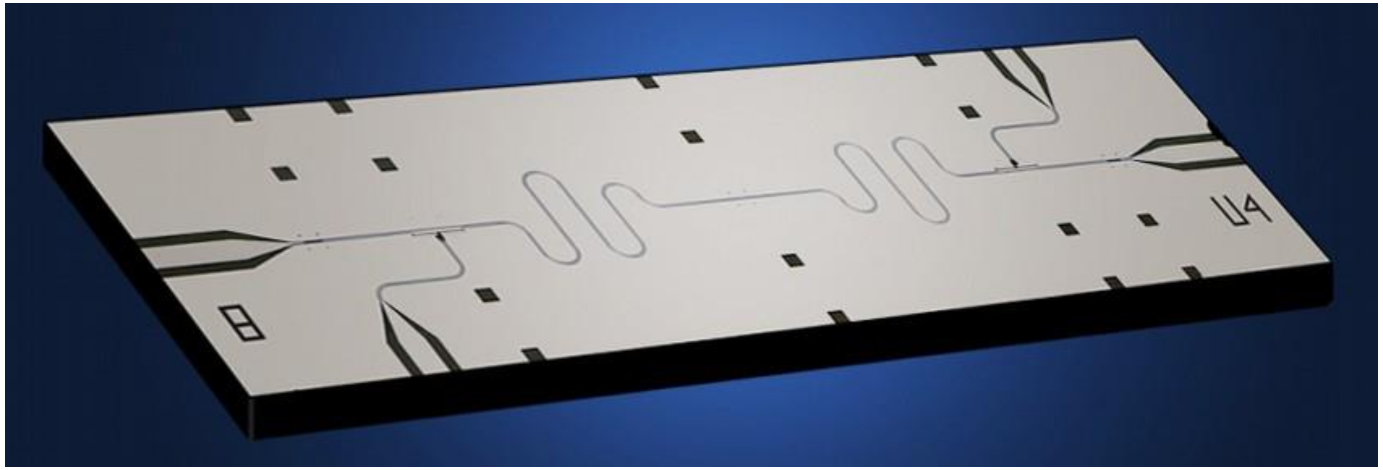
Confined electromagnetic field among two or more conducting plates, on an isolating substrate.



Strong coupling

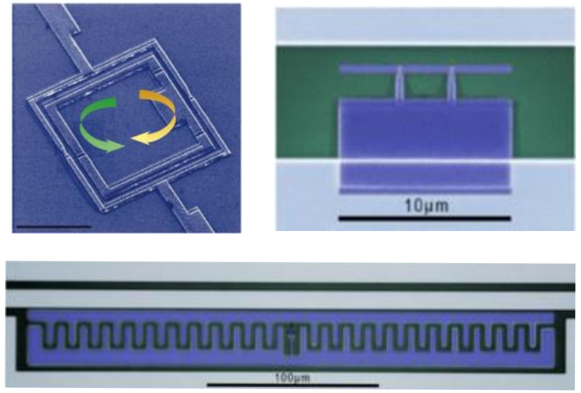


A. Wallraff et al, Nature 431, 162 (2004)

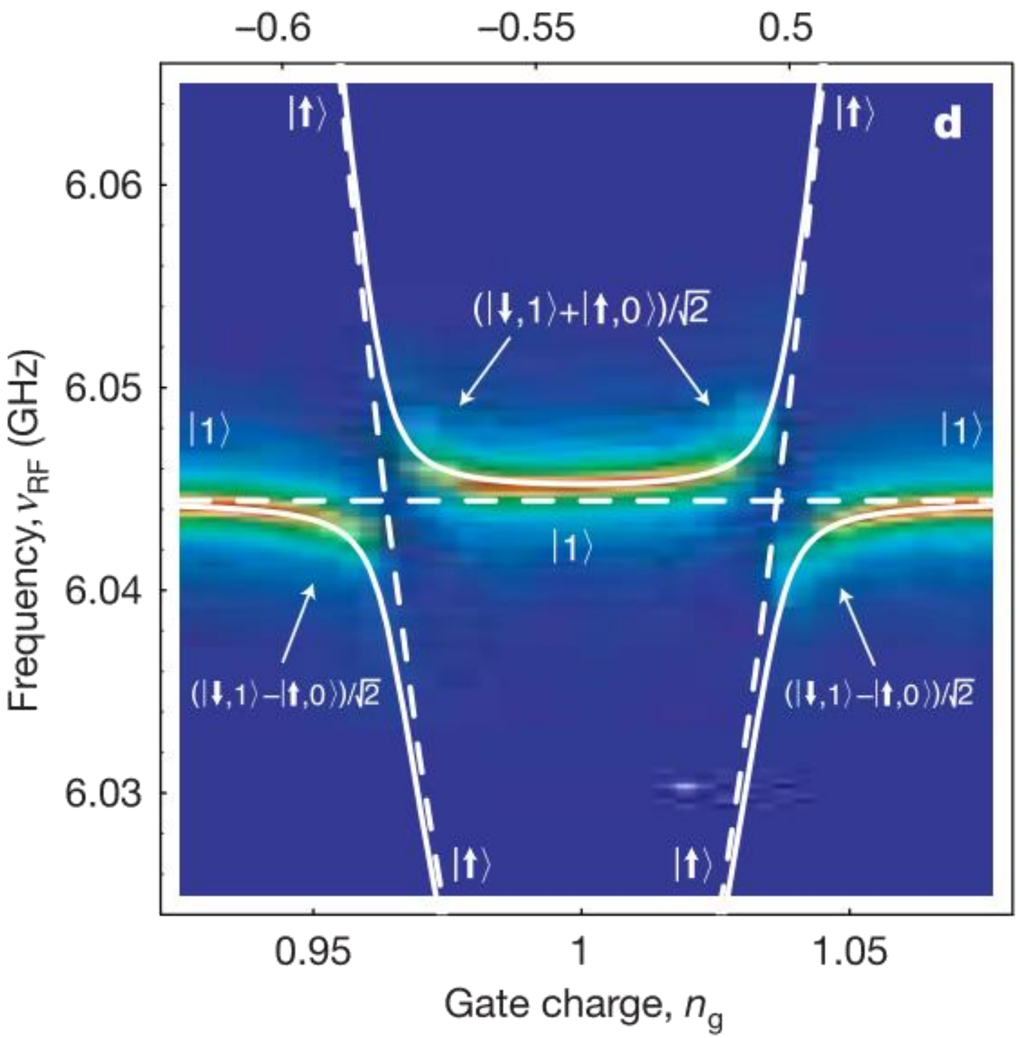


Jaynes-Cummings model

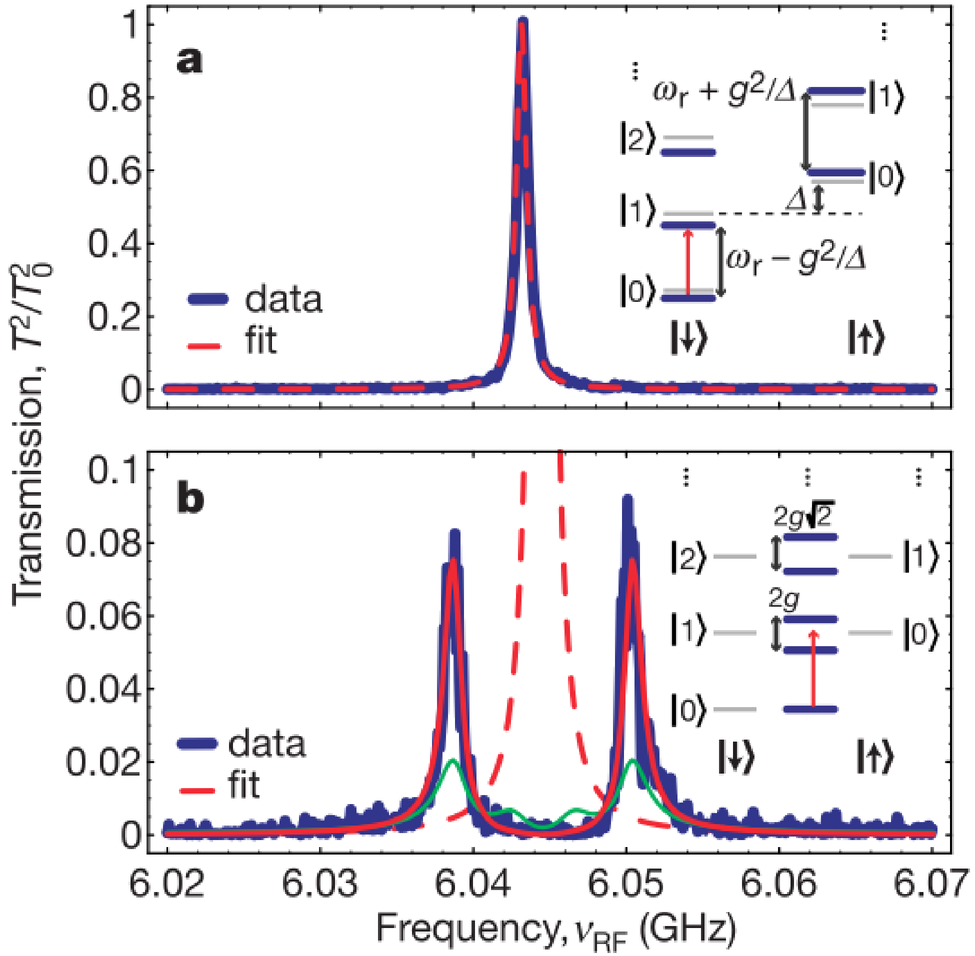
$$\mathrm{H} = \frac{\Delta}{2}\,\sigma^z + \frac{\epsilon}{2}\,\sigma^x + \omega a^+ a$$
$$+g\,(\sigma^+ a + \sigma^- a^+)$$



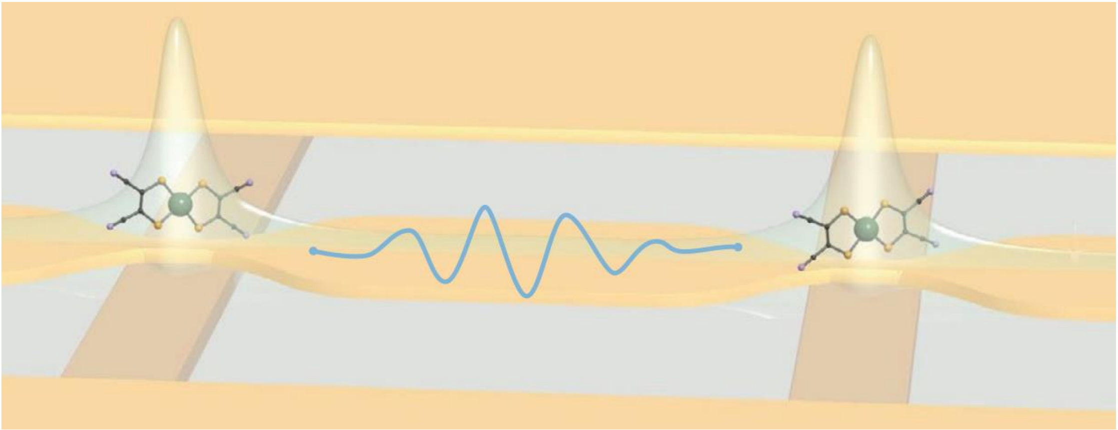
Strong coupling

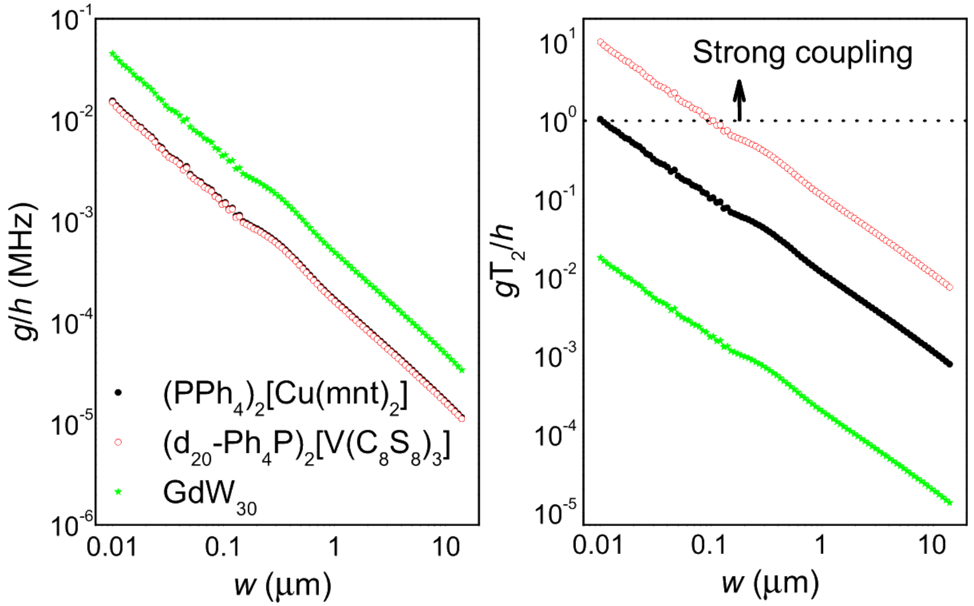


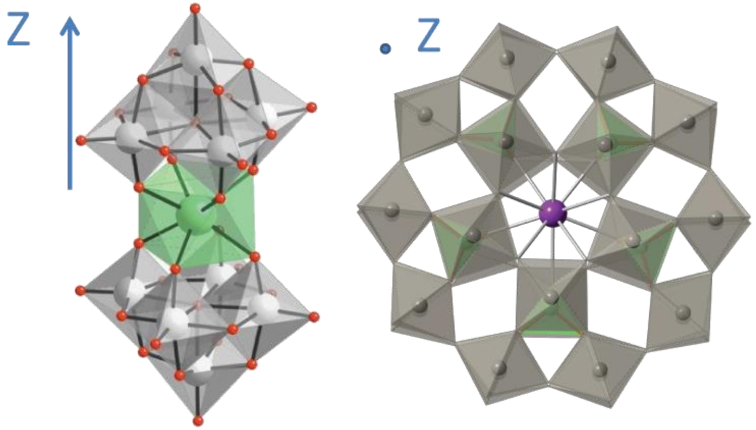
A. Wallraff et al, Nature 431, 162 (2004)



Molecular nanomagnets







$[HoW_{10}O_{36}]^{9-}$

Shiddiq et al. [37]

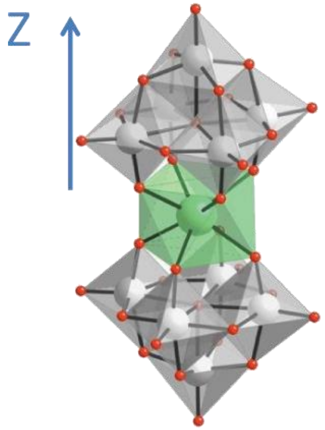
$[GdP_5W_{30}O_{110}]^{12-}$

Jenkins et al. [39]

Towards single-molecule strong coupling.
μ-wave control and strong coupling with ensembles already there.

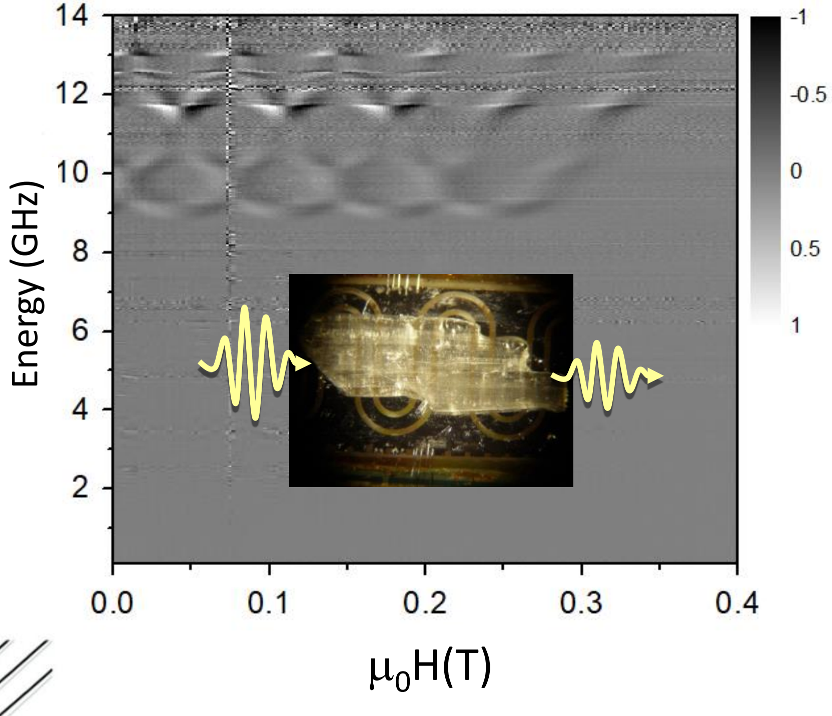
A. Gaita-Ariño et al, Nat. Chem. (2019)
M.D. Jenkins et al Dalton Trans. (2016)

Experimental realizations

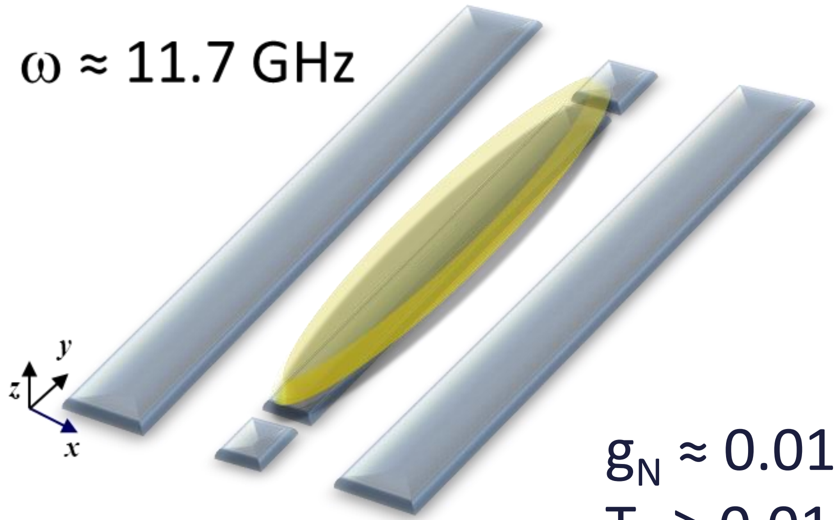


$[HoW_{10}O_{36}]^{9-}$

Shiddiq et al. [37]

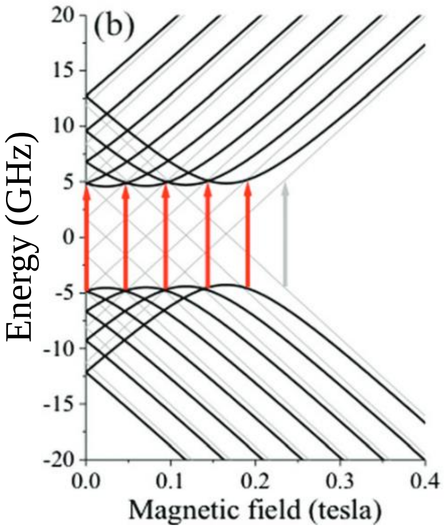


$\omega \approx 11.7$ GHz



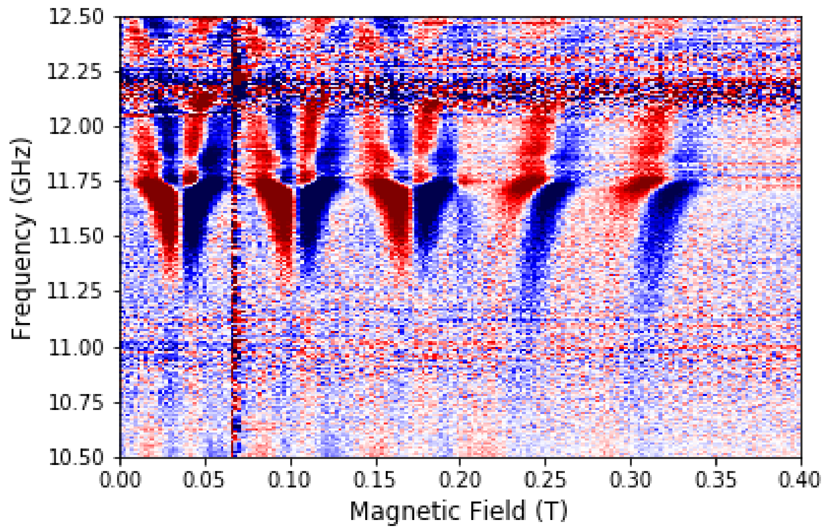
$g_N \approx 0.01$ GHz

$T_2 \geq 0.01\ \mu s$

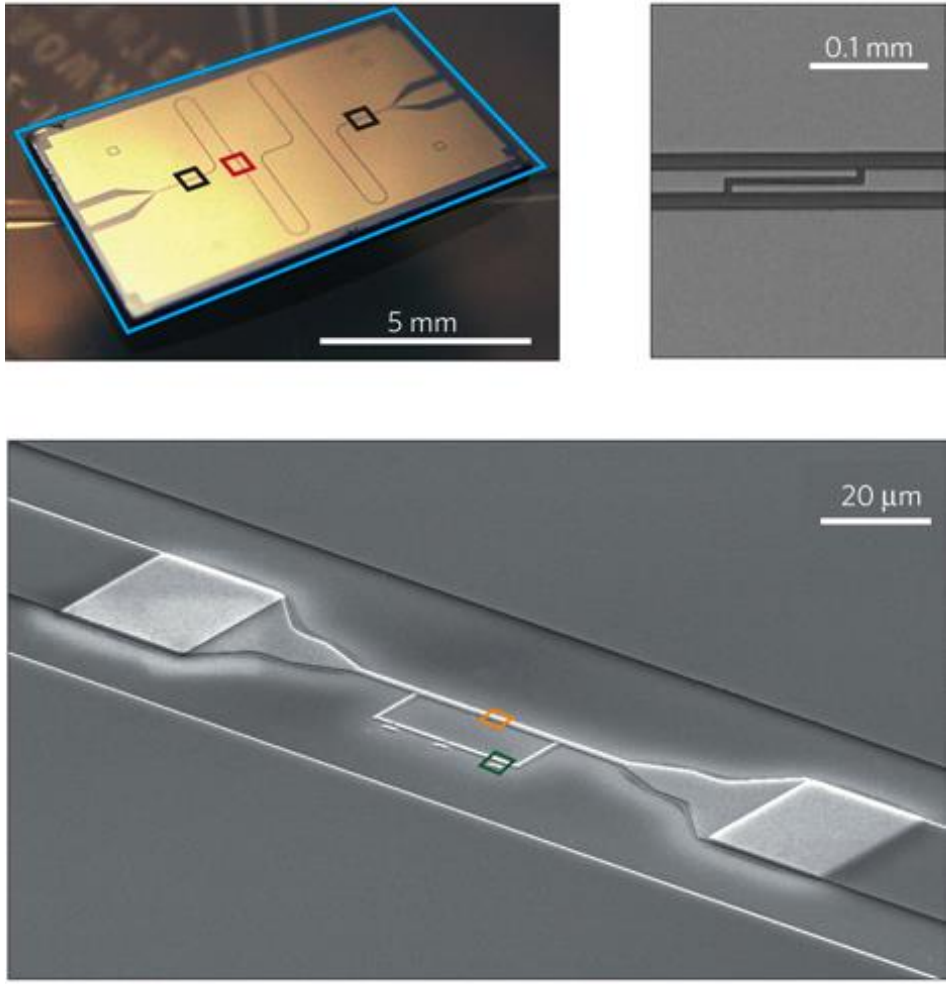


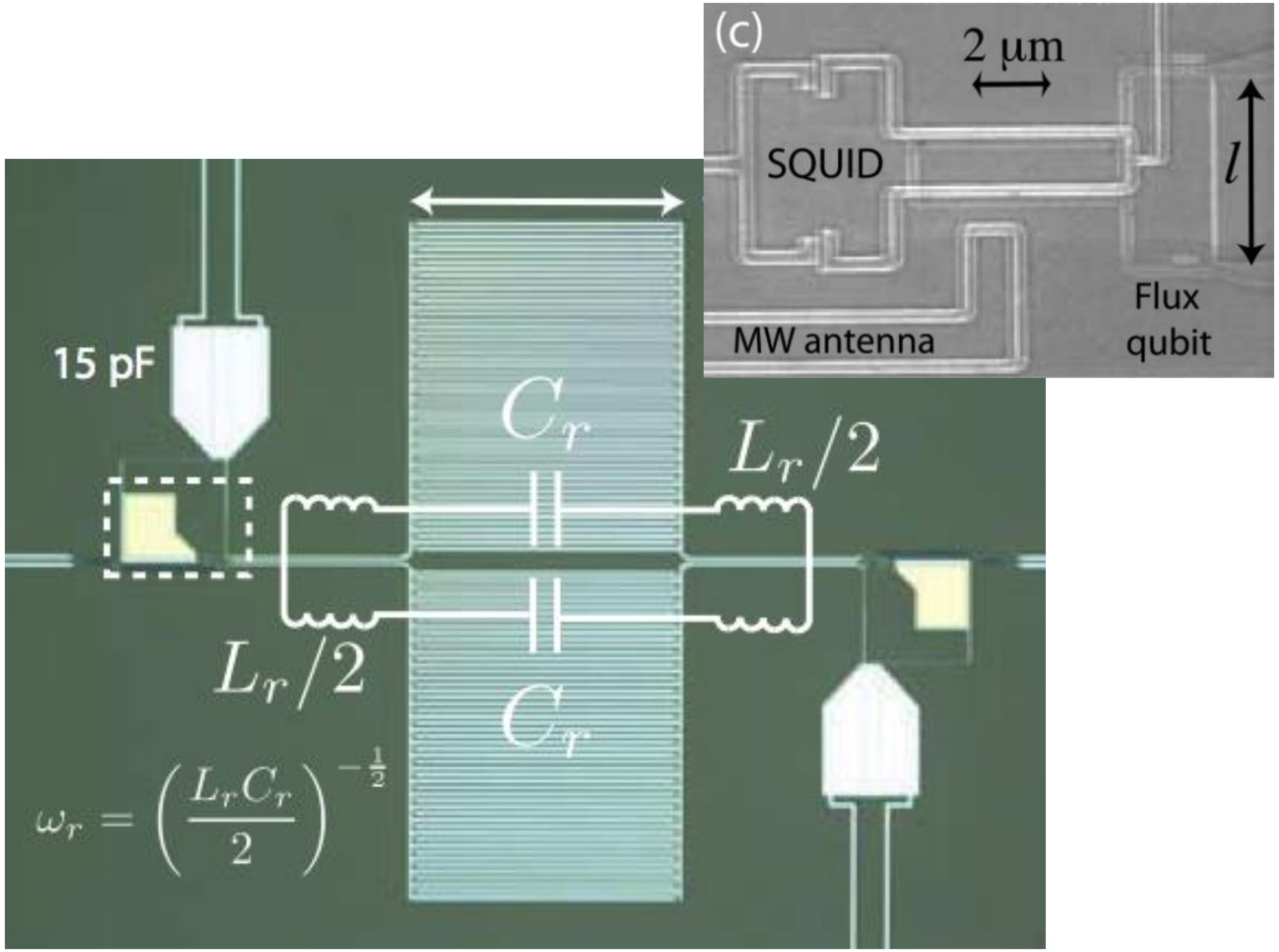
From spectroscopy assisted by coplanar waveguides, to qubit-cavity coupling in c-QED

Also: a many-body Ising model that talks to the superconductor!



Ultrastrongly coupled circuit-QED

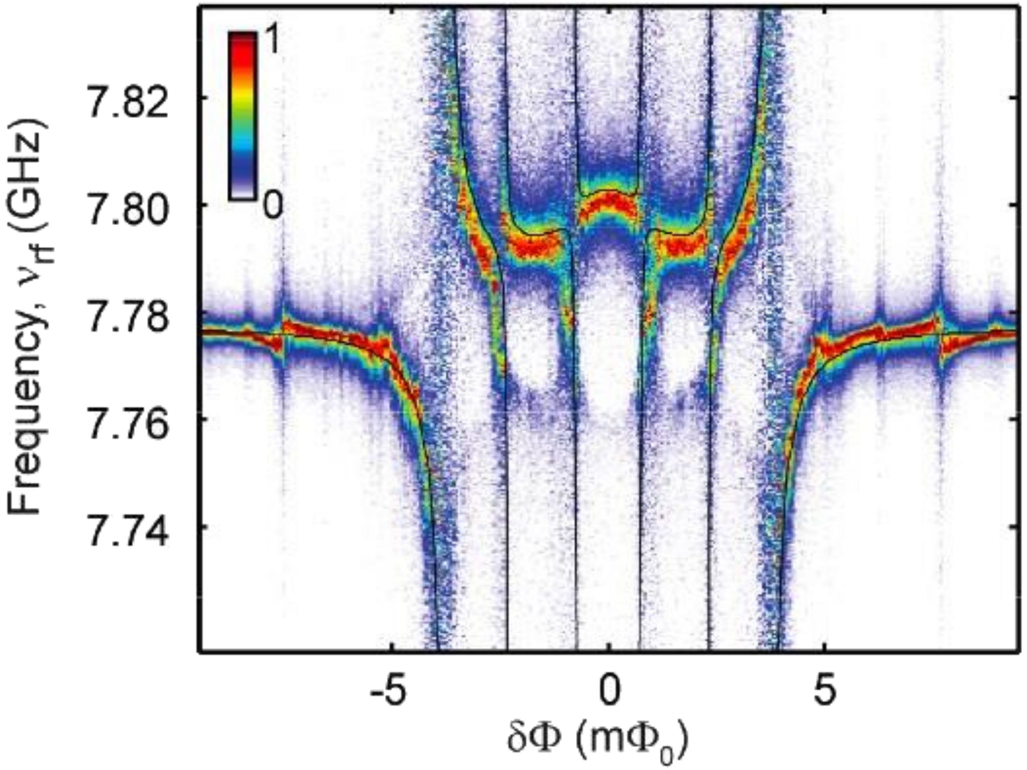


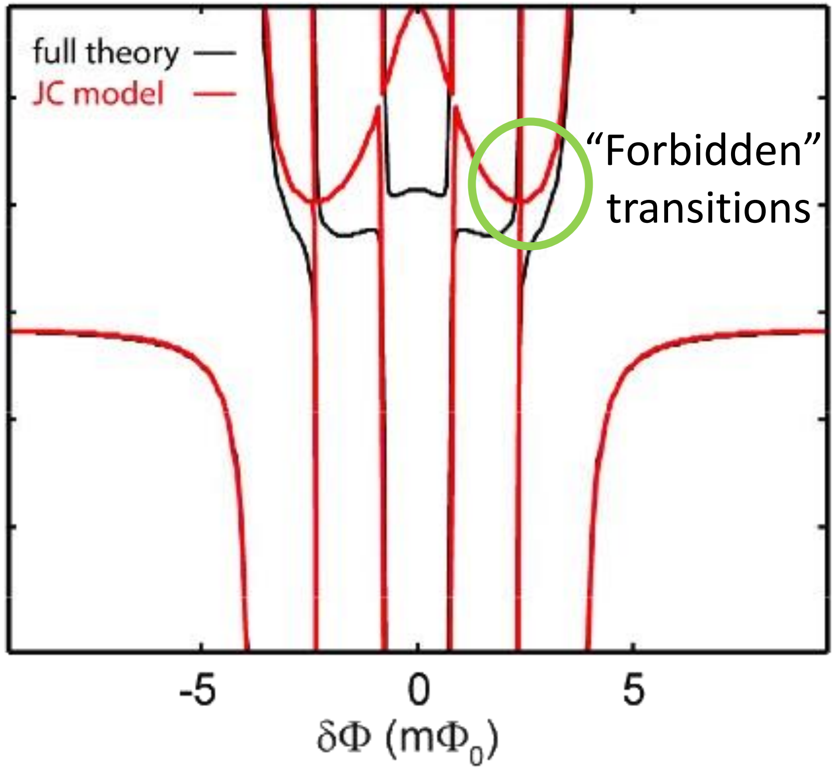


*T. Niemczyk et al, Nature Physics **6**,772–776 (2010)*

*P. Forn-Díaz et al PRL **105** 237001 (2010)*

Non-RWA spectra

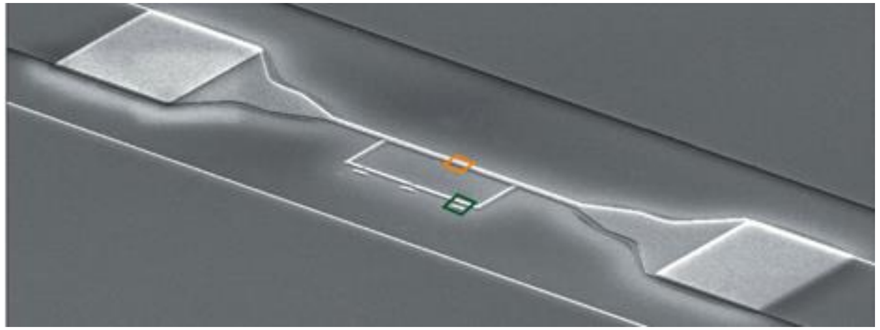




$$\frac{g}{\Delta} = 12\%$$

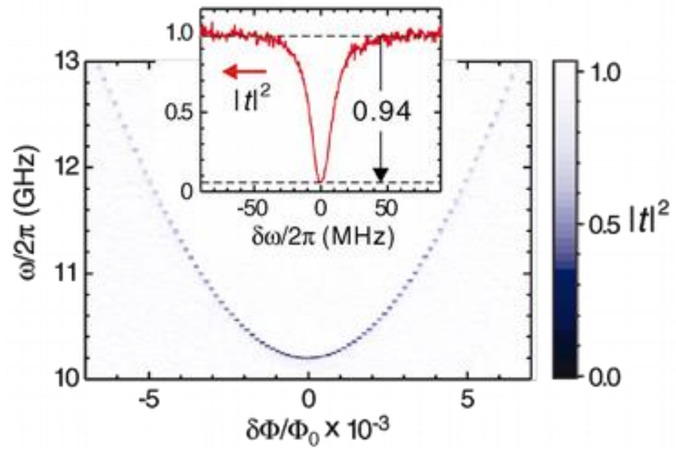
RWA $g(\sigma^+ a + \sigma^- a^\dagger)$

Rabi $g\sigma^x(a + a^\dagger)$

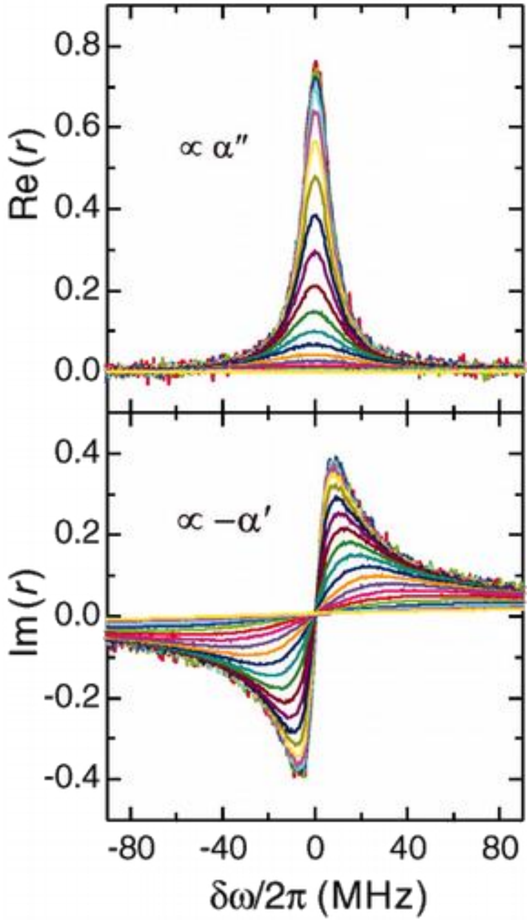


T. Niemczyk et al, Nature Physics ***6****,772–776 (2010)*

Propagating photons



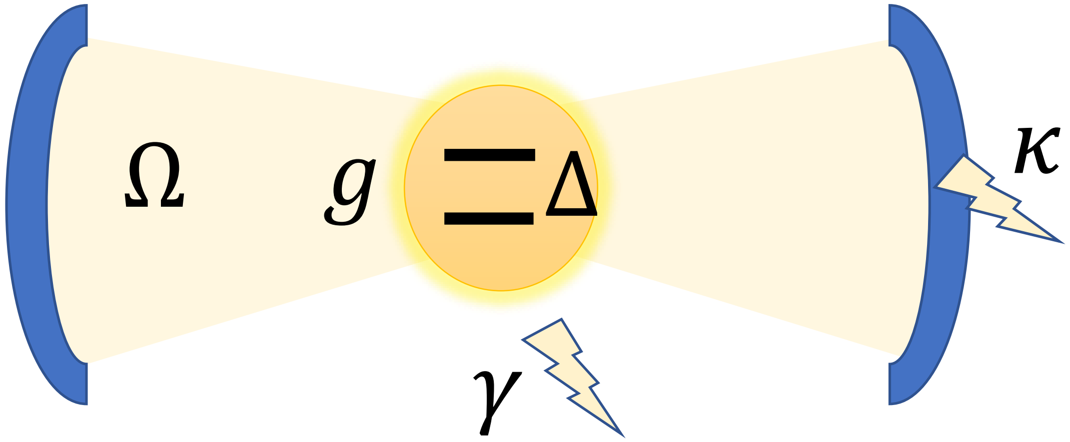
$$r = r_0 \frac{1}{\Gamma_1/2 + \Gamma_\phi - i\delta\omega}, \quad t = 1 - r$$



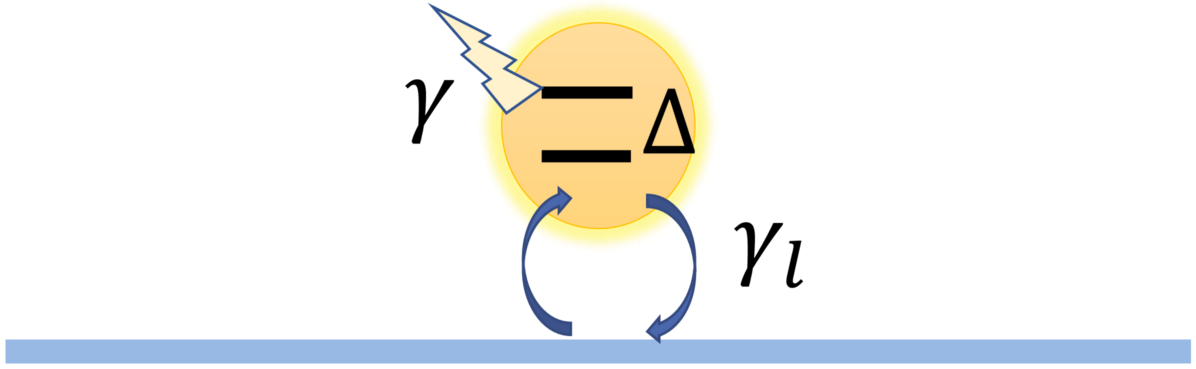
Resonance fluorescence of a signle artificial atom
O. Astafiev et al, Science 12, 327 (2010)

Open line USC?

Cavity-QED



Open systems



Strong coupling:

$$g \gg \kappa, \gamma$$

Ultrastrong coupling

$$g \simeq \Delta, \omega \gg \kappa, \gamma$$

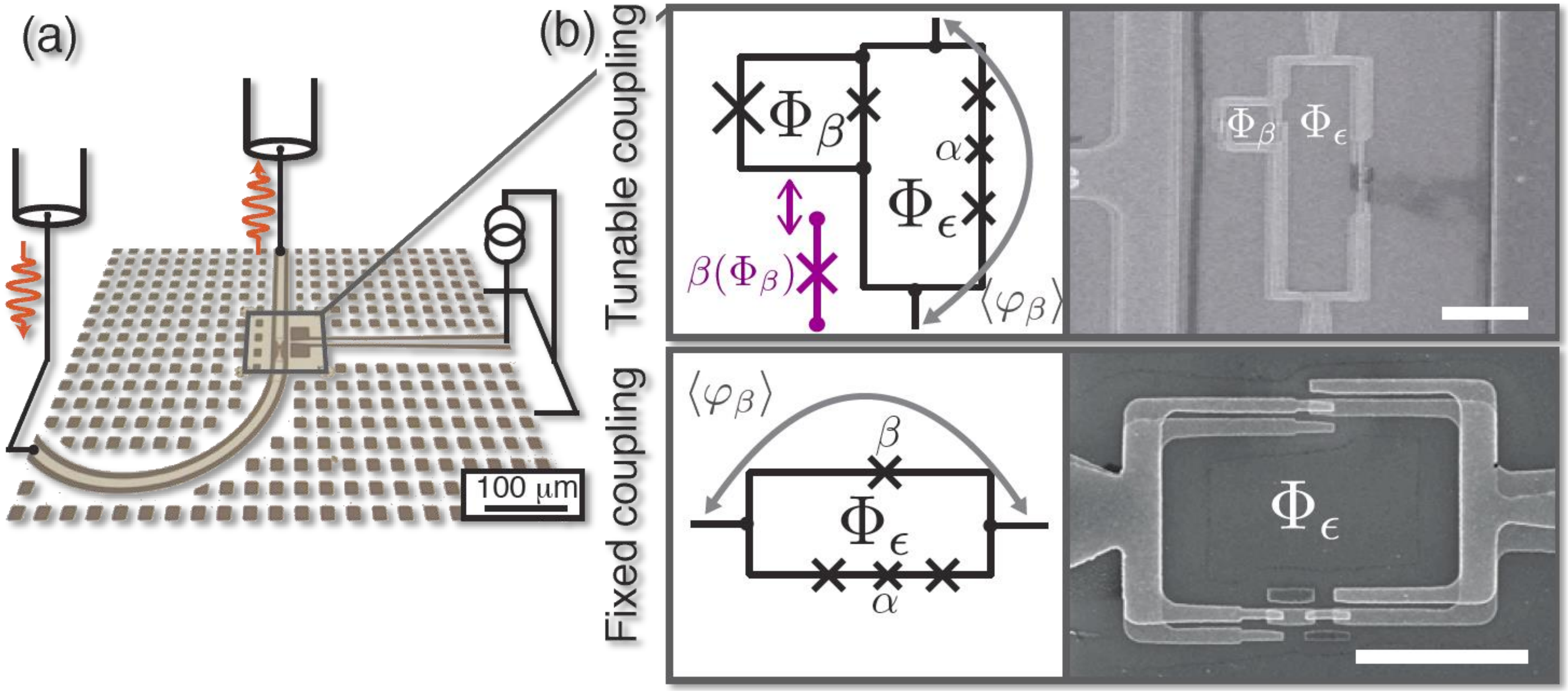
Strong coupling:

$$\gamma_l \gg \gamma$$

Ultrastrong coupling

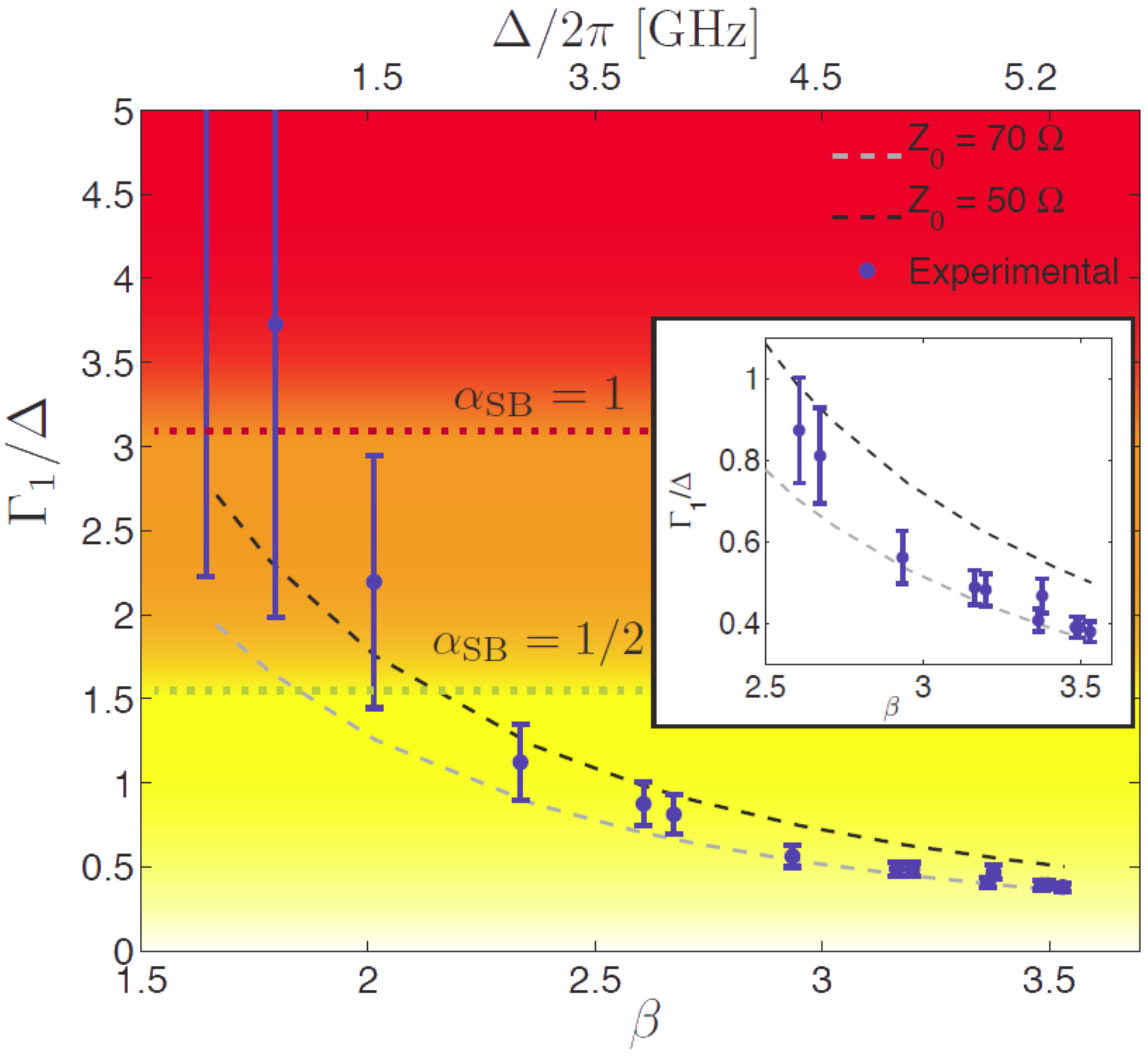
$$\gamma_l \simeq \Delta, \omega \gg \gamma$$

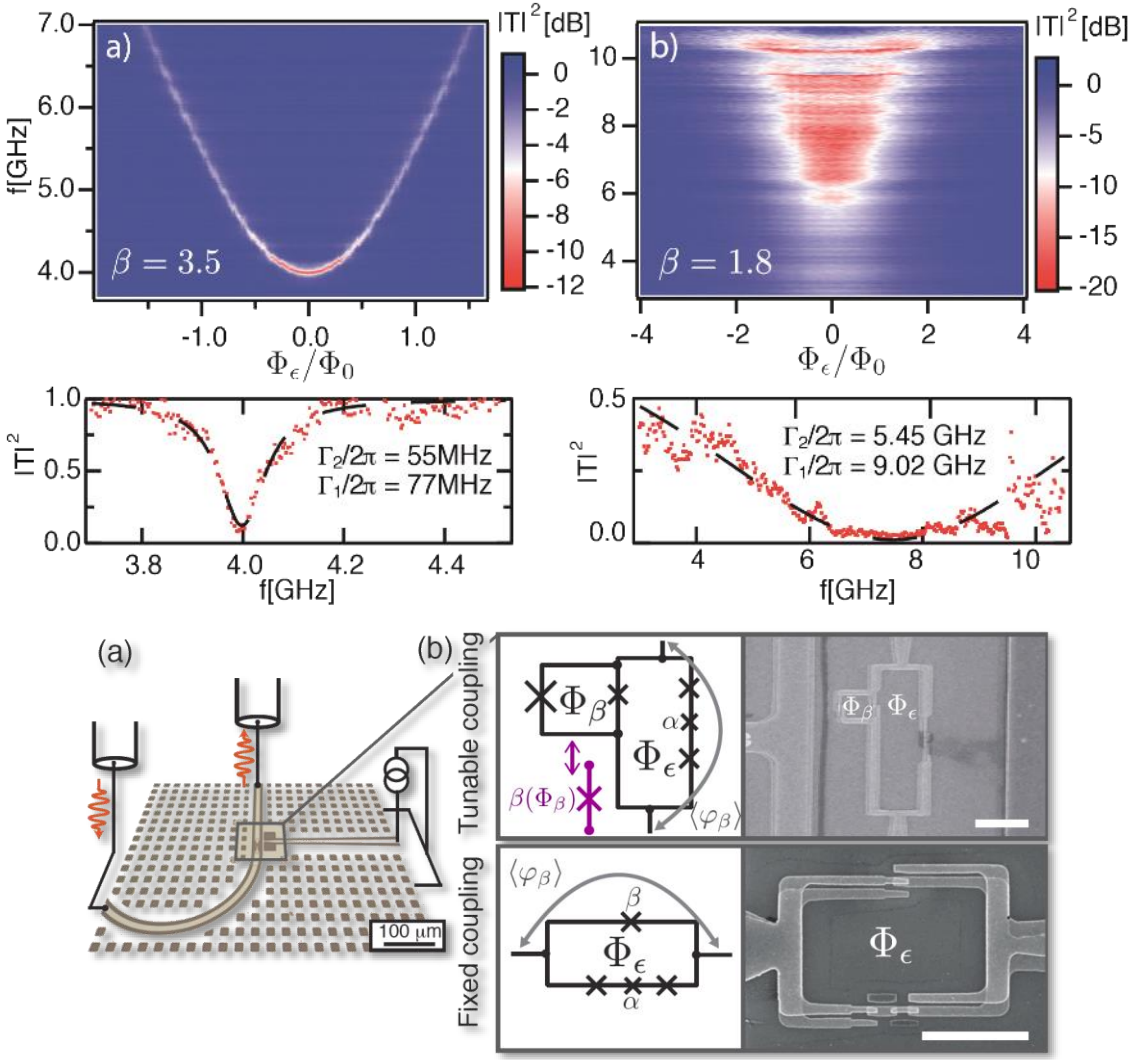
Ultrastrong coupling in open lines



P. Forn Díaz et al, Nat. Phys. 13, 39 (2017)

Ultrastrong coupling in open lines





P. Forn Díaz et al, Nat. Phys. 13, 39 (2017)

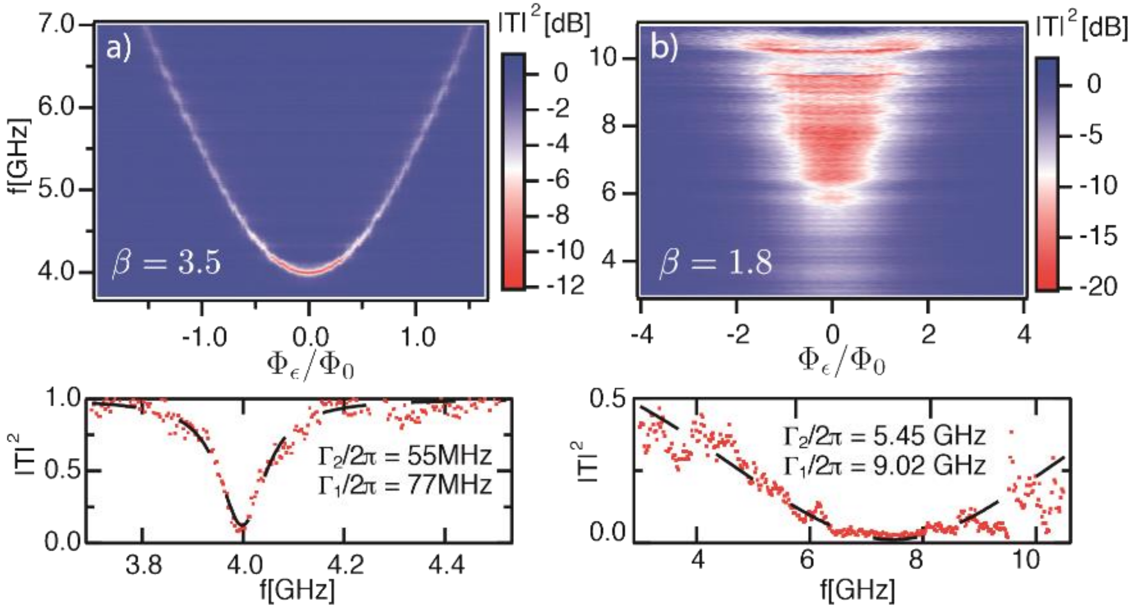
Quantum microwave photonics

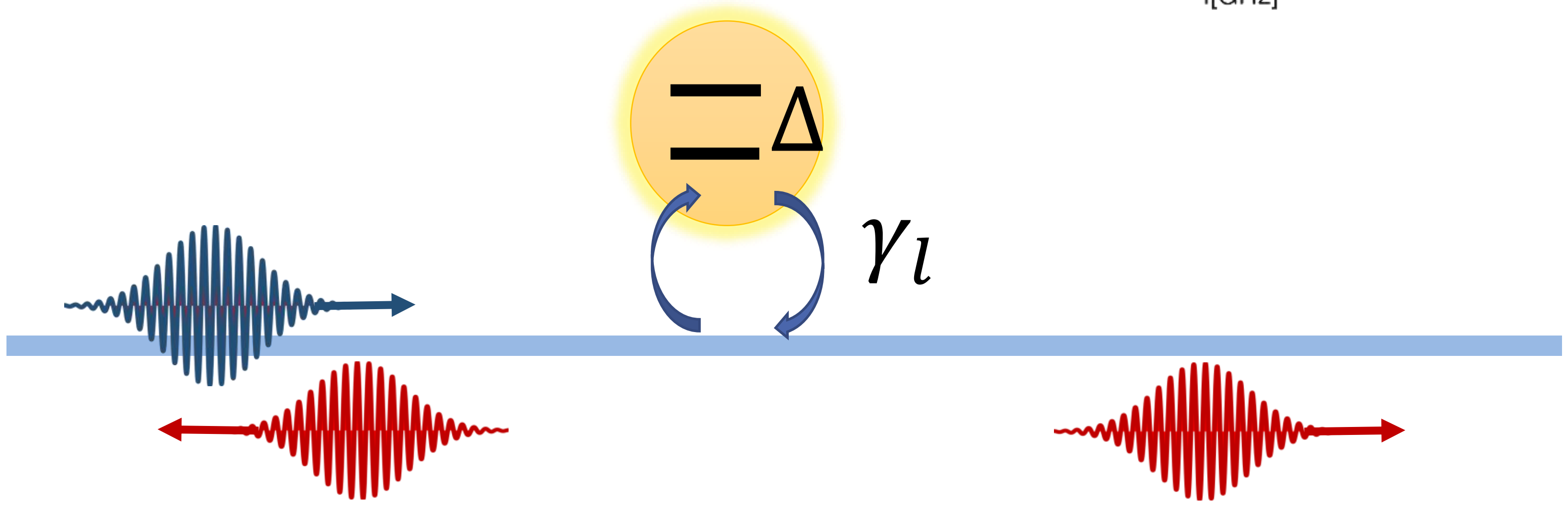
Indirect probes of the system dynamics

$$S_{out,in} = \langle \psi_{out} | U | \psi_{in} \rangle$$

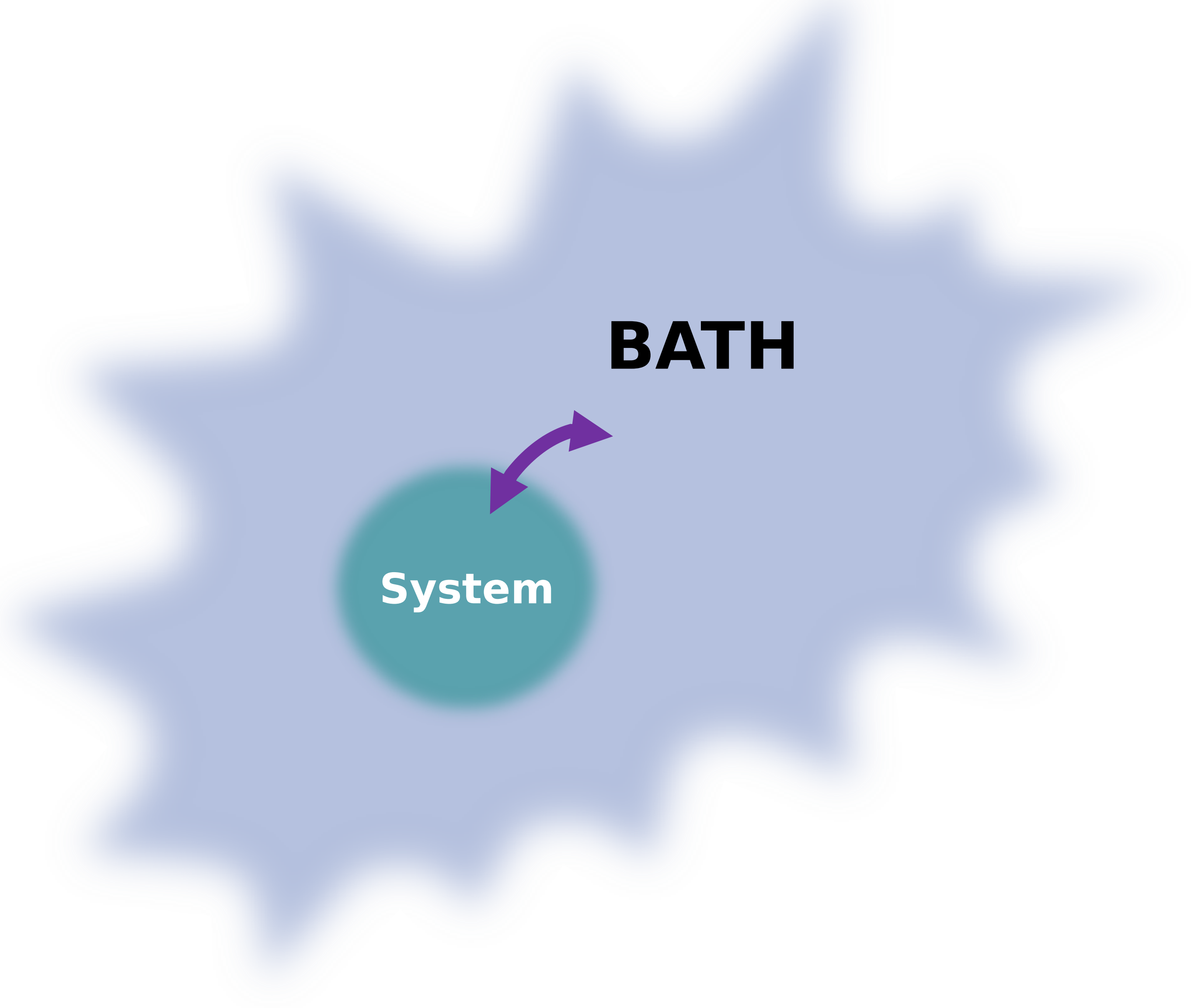
For instance,

$$S_{\omega_{out},\nu_{in}} = \langle g, 0 | a_{out}^{+} U a_{in} | g, 0 \rangle$$





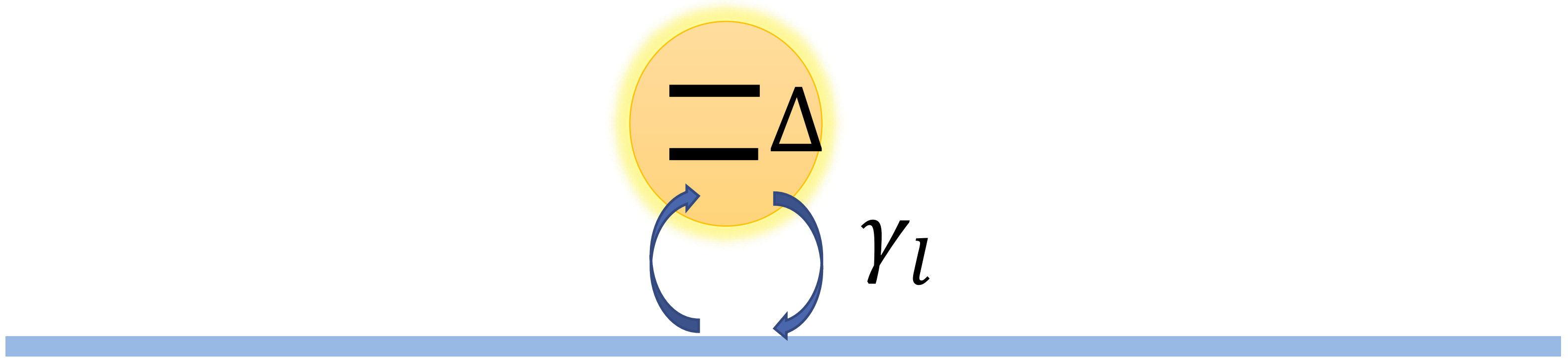
Beyond usual open quantum systems



- Frontier between the system and bath diffuses (correlations)
- Usual approximations break down, but others may emerge
- **Bath influenced by the system.**
- We can **use the bath to control and monitor the system**.

Theoretical tools

Spin-boson model



$$H_P = \sum_k \omega_k a_k^\dagger a_k + \frac{1}{2}\Delta\, \sigma^z + \sigma^x \sum_k (g_k a_k^\dagger + g_k^* a_k)$$

Photons **Emitter** **Dipolar coupling**

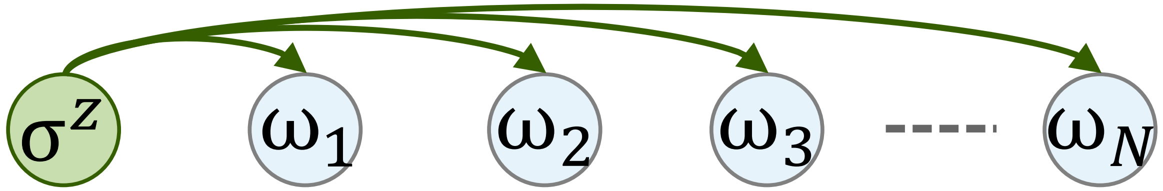
Spectral function (Ohmic)

$$J(\omega) = 2\pi \sum_k |g_k|^2 \delta(\omega - \omega_k) \sim \pi\alpha\omega^1$$

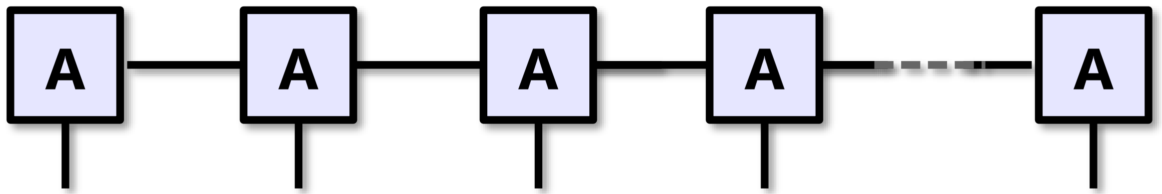
Ultrastrong Coupling (USC)

$$\frac{\Gamma}{\Delta} \sim 2\pi\alpha \sim 0.1$$

Tool #1: Matrix Product State ansatz

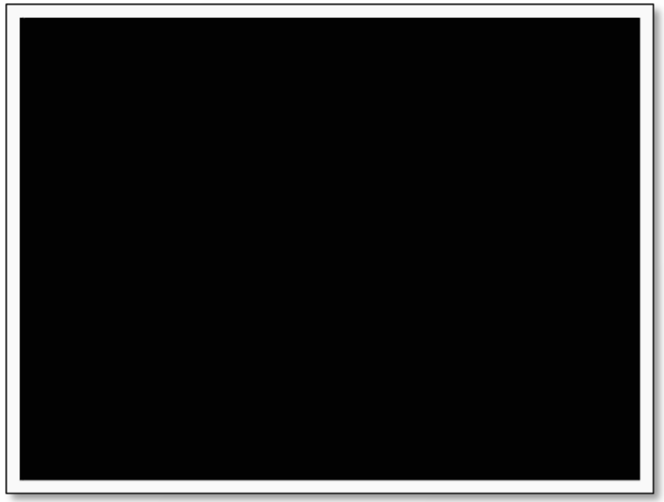


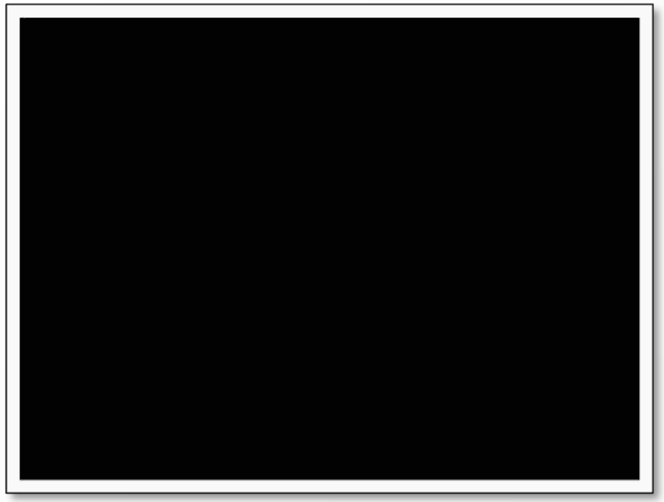
$$H = \frac{\Delta}{2}\sigma^z + \sum_k \omega_k a_k^+ a_k + \sum_k \sigma^x (g_k a_k^+ + \mathrm{H.c.})$$

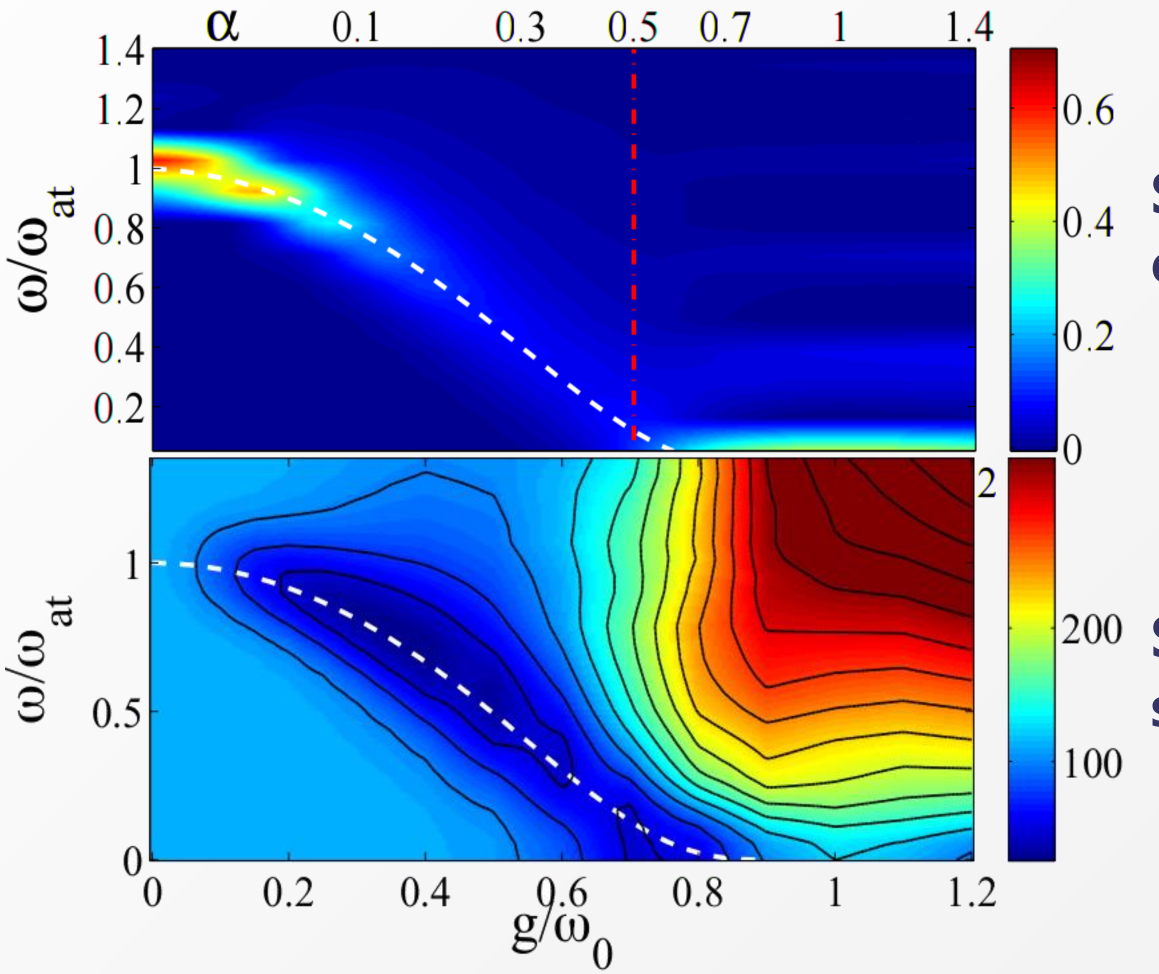


$$|\,\psi\rangle = \sum_{s,\vec{n}} tr\left[A_1^{s_1} A_2^{n_2} \cdots A_L^{n_L}\right] |\, s_1, n_2 \ldots n_L\rangle$$

Nonlocal interactions with MPS: *J. J. García-Ripoll, New J. Phys.* ***8*** *305 (2006)*







Spontaneous emission

Single-photon spectroscopy

B. Peropadre et al. PRL 111, 243602 (2014)

Tool #2: Polaron Hamiltonian

$$H_P = U_P H U_P^\dagger = \frac{\widetilde{\Delta}}{2}\sigma^z O_{-f}^\dagger O_f + \sum_{kl} J_{kl} a_k^\dagger a_l + \sigma^x \sum_k (G_k a_k^\dagger + G_k^* a_k)$$

Self-consistent calculation in position space

$$U_P = e^{\sigma^x \frac{1}{\sqrt{2}} \sum_k (f_k a_k^\dagger - f_k^* a_k)}$$

$$\vec{f} = \left(J + \widetilde{\Delta}\right)^{-1} \vec{g}$$

$$\widetilde{\Delta} = \Delta\, \mathrm{e}^{-2\sum_k |f_k|^2}$$

$$f_k = \frac{g_k}{\omega_k + \widetilde{\Delta}}$$

$$\widetilde{\Delta} = \Delta\, \mathrm{e}^{-2\sum_k |f_k|^2}$$

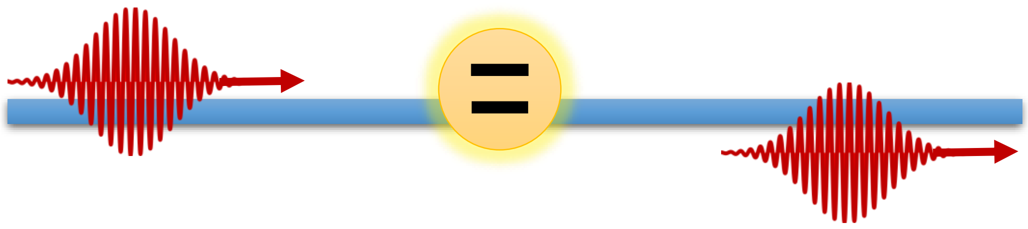
$$G_k = \widetilde{\Delta} f_k$$

Disentangles emitter from photon vacuum

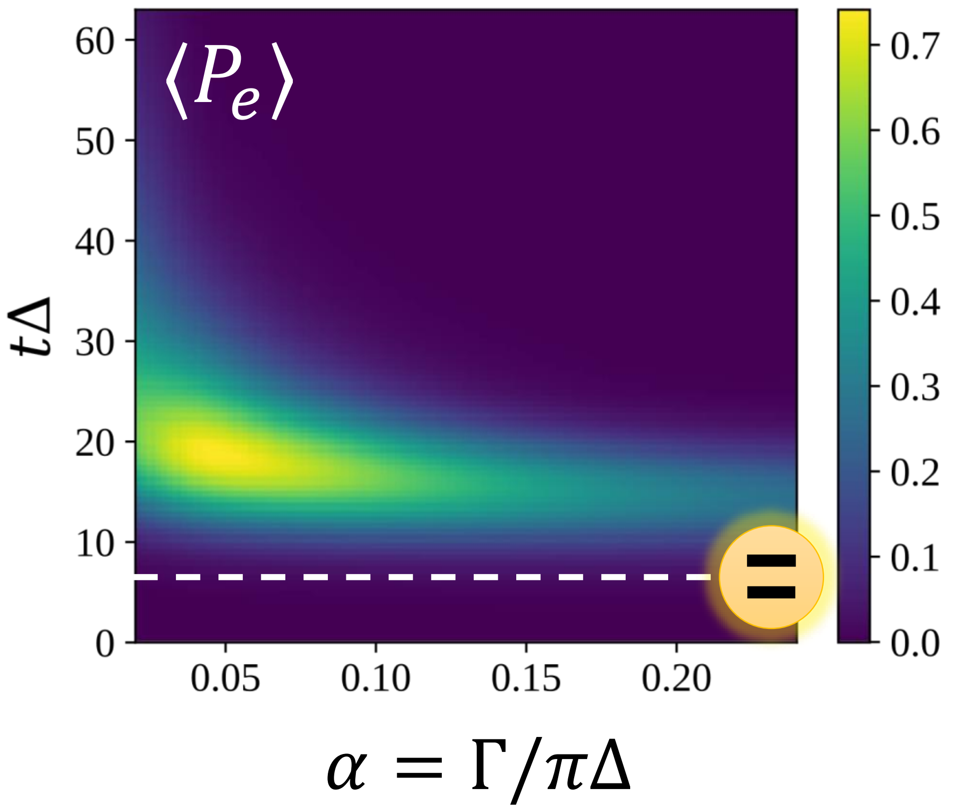
$$O_f = e^{2\sigma^x \sum_k f_k a_k}$$

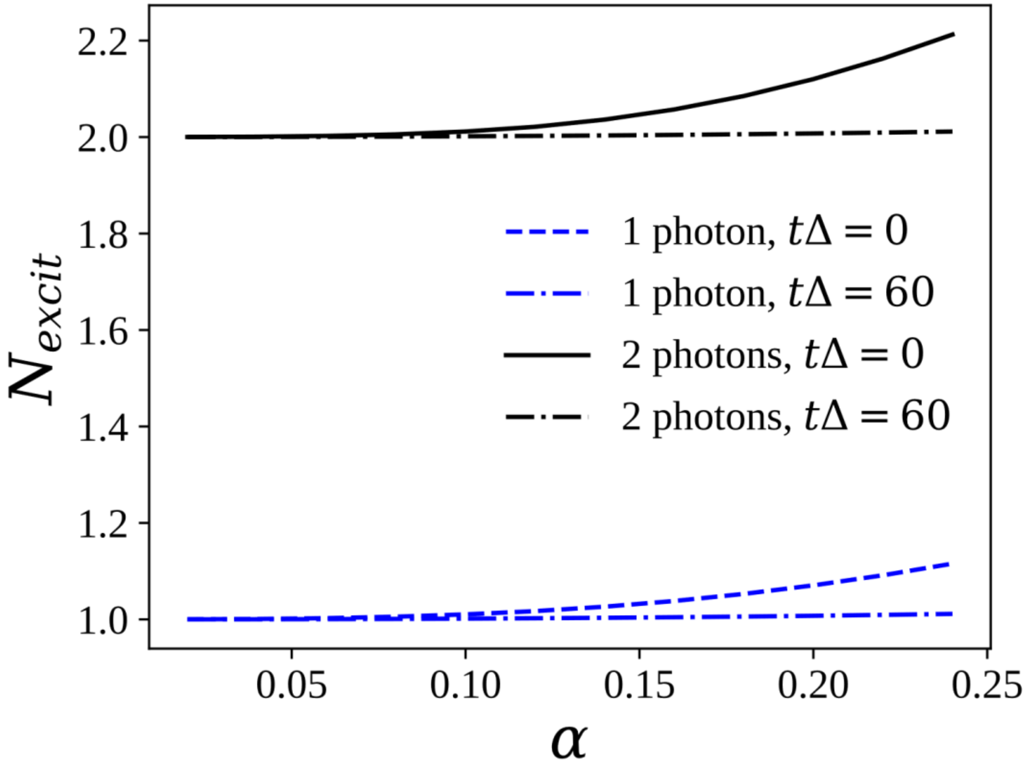
Approximately conserved excitations

1,2 photons



$$N_{excit} = \frac{1}{2}(\sigma^z + 1) + \sum_k a_k^\dagger a_k$$





Tool #3: Truncated polaron model

$$H_P = \frac{\widetilde{\Delta}}{2}\sigma^z O_{-f}^{\dagger} O_f + \sum_k \omega_k a_k^{\dagger} a_k + \sigma^x \sum_k \widetilde{\Delta}\left(f_k a_k^{\dagger} + f_k^* a_k\right)$$

$$H_P^{(2)} = \frac{\widetilde{\Delta}}{2}\sigma^z + \sum_k \omega_k a_k^{\dagger} a_k + 2\widetilde{\Delta}\Theta\left(\sigma^- b_0^{\dagger} + b_0 \sigma^+\right) - 2\widetilde{\Delta}\Theta\sigma^z b_0^{\dagger} b_0$$

$$- 2\widetilde{\Delta}\Theta\left(\sigma^z \sigma^+ b_0^{\dagger} b_0 b_0 + b_0^{\dagger} b_0^{\dagger} b_0 \sigma^- \sigma^z\right)$$

$$- 2\widetilde{\Delta}\Theta\sigma^z\left(b_0^{+} b_0^{+} b_0 b_0 - b_0^{+} b_0\right)$$

+ non-RWA

V. Paulisch, T. Shi, JJGR, arXiv:1810.08439

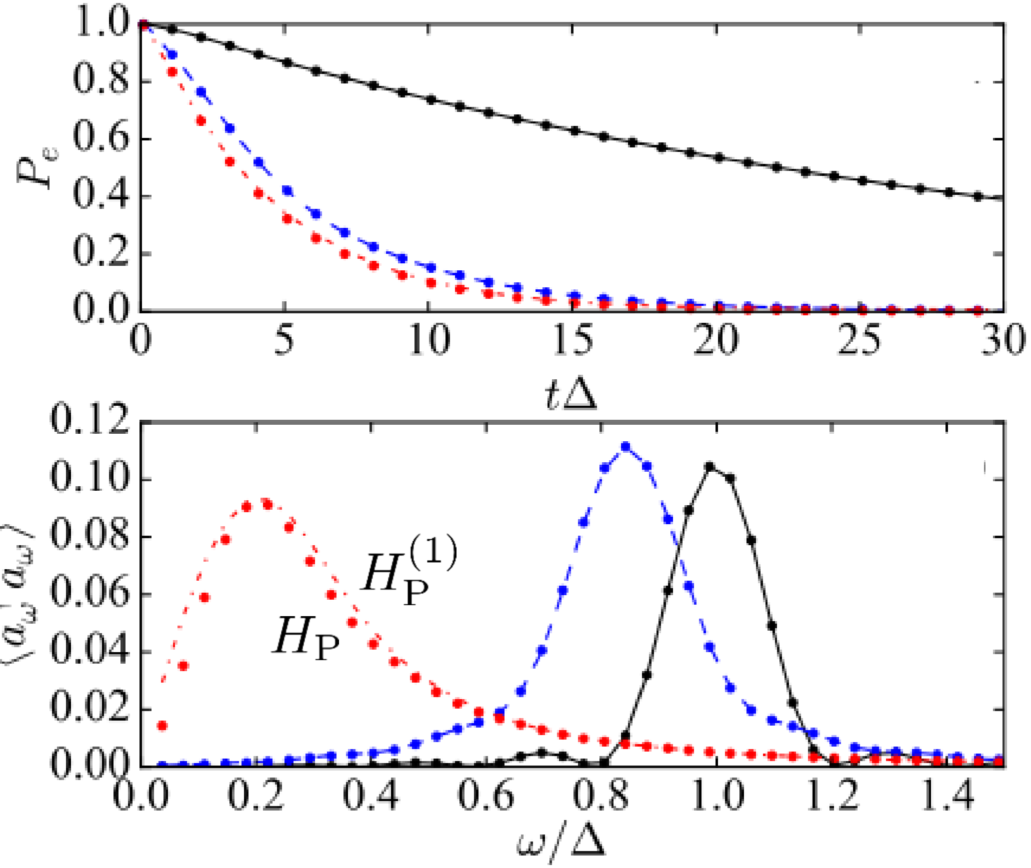
Single-excitation manyfold (RWA!)

$$H_{\rm P}^{(1)} = \frac{\tilde{\Delta}}{2}\sigma^z + \sum_k \omega_k a_k^\dagger a_k + \sum_k \frac{2}{\sqrt{L}}(G_k \sigma^- a_k^\dagger + G_k^* a_k \sigma^+) + V_{\rm local}$$

We compare MPS simulation with the subspace of one excitation:

- The model becomes RWA automagically.
- The numerical simulations for spontaneous emission dynamics and spectra agree with the original model up to large α ~ 0.35 (red)

Tao Shi, Yue Chang, JJGR, PRL ***120****, 153602 (2018)*



Full analytical computation

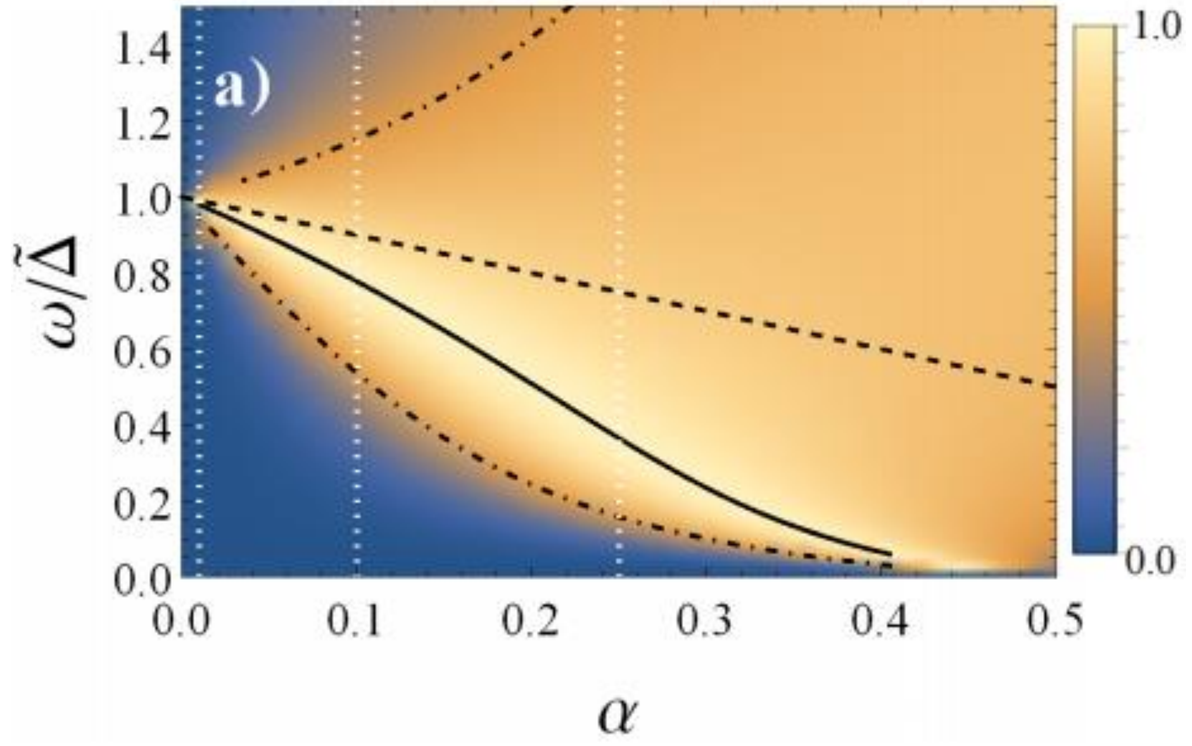
$$S_{f,i} = \lim_{t\to\infty} e^{-i(E_f - E_i)t} \langle \psi_f | U(t,0) | \psi_i \rangle$$

Dyson series

Exact resummation

$$S_{f,i} = S_{f,i}^{uncorr} - 2\pi i \delta\left(E_f - E_i\right) T_{f,i}$$

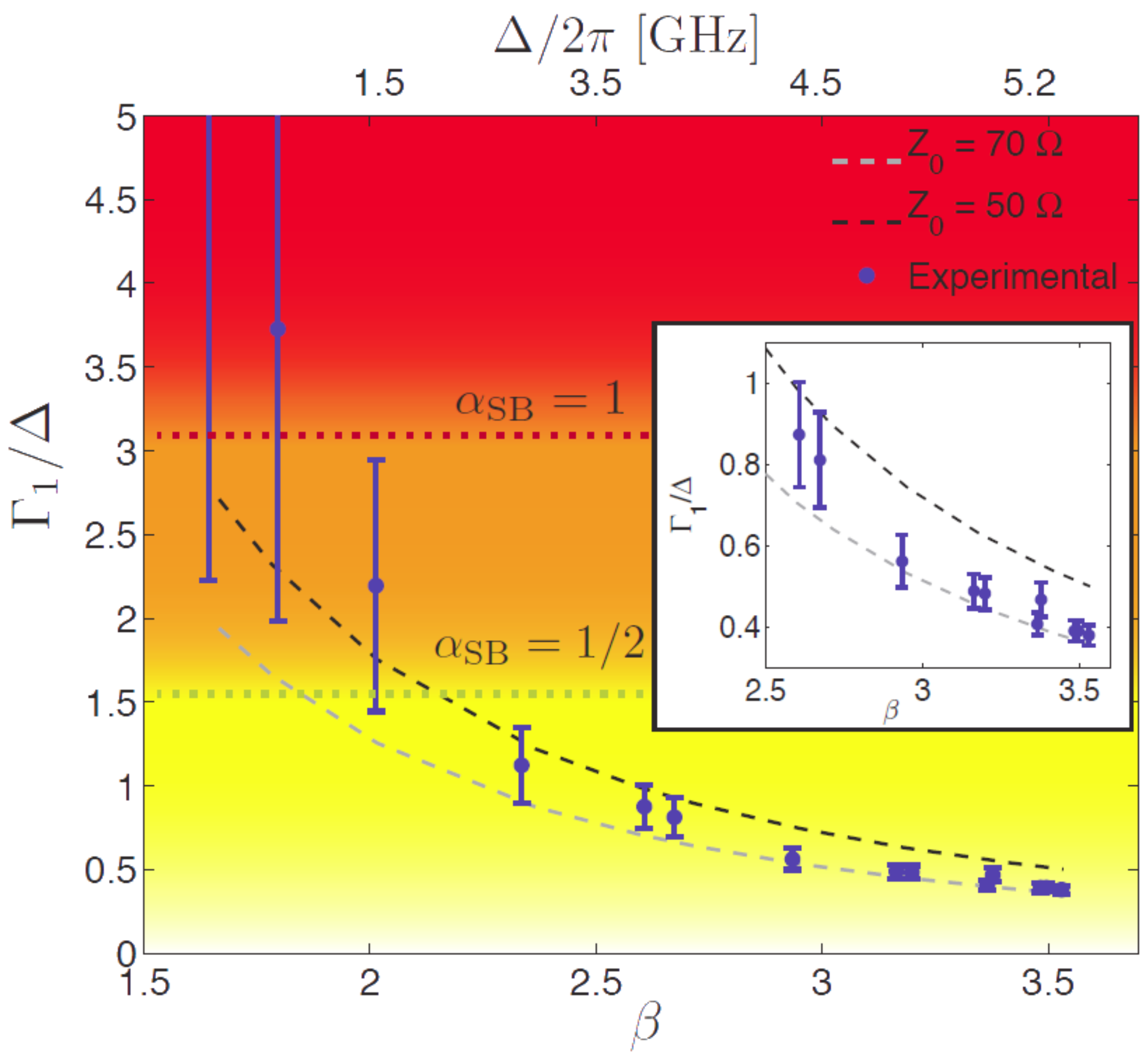
Resonance spectrum (reflection)

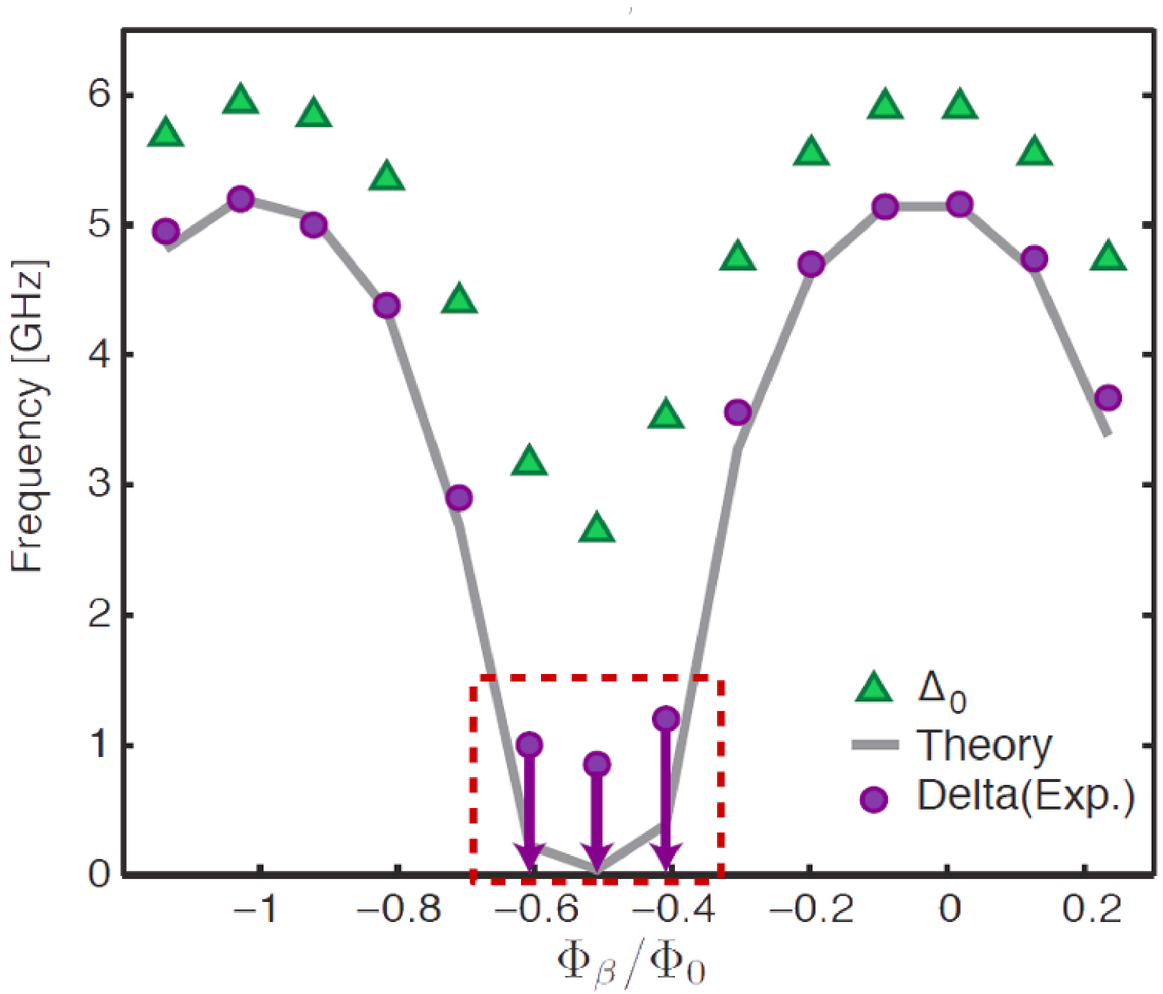


T. Shi, Y. Chang, JJGR, PRL ***120****, 153602 (2018)*

V. Paulisch, T. Shi, JJGR, arXiv:1810.08439

Fitting to experiments





P. Forn Díaz et al, Nat. Phys. 13, 39 (2017) zenodo

SeeQ – Self Explanatory Quantum Optic Library

https://github.com/juanjosegarciaripoll/seemps

DOI 10.5281/zenodo.3470760

juanjosegarciaripoll / seeq

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See Quantum - Self-explanatory library for Quantum Optics and Quantum Mechanics

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41 commits | 1 branch | 0 packages | 1 release | 1 contributor | MIT

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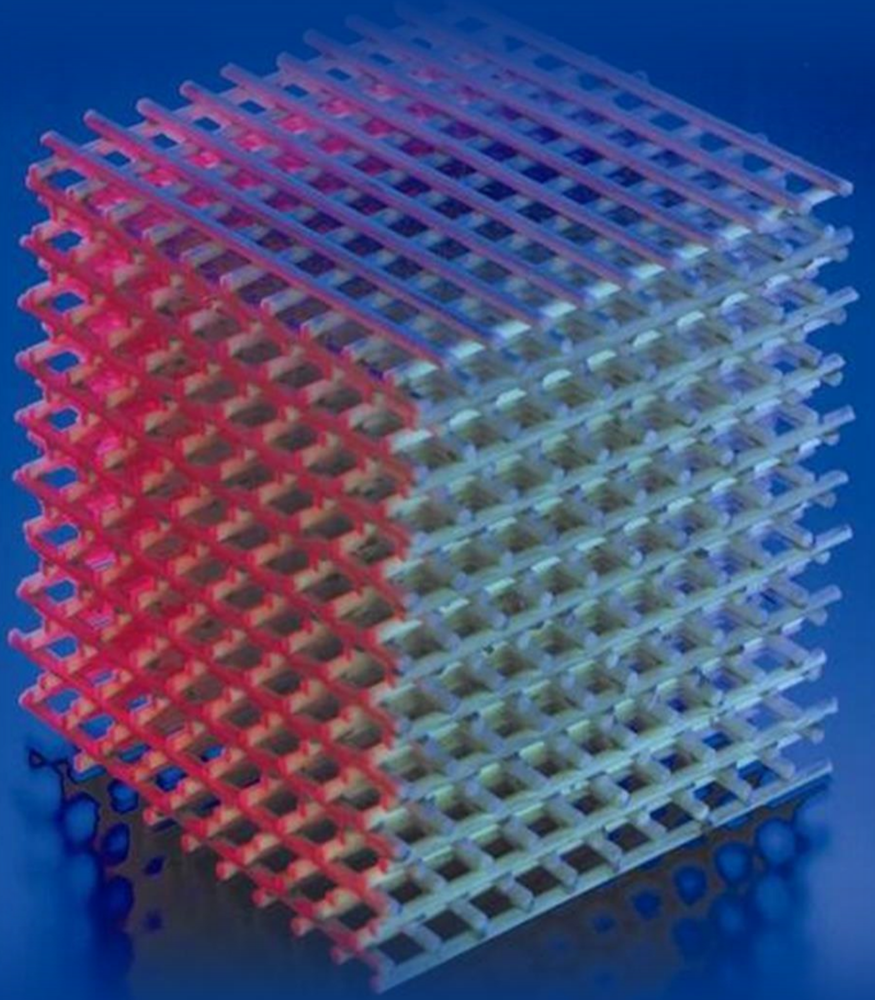
juanjosegarciaripoll Detail how to cite this work. Latest commit 17d2639 on 3 Oct

figures	Added missing figures for the transmon file.	4 months ago
seeq	Added a function to plot fields on a lattice	2 months ago
.gitignore	Initial commit	4 months ago
00 Introduction.ipynb	Renamed and ordered notebooks	2 months ago
1a Time evolution.ipynb	Renamed and ordered notebooks	2 months ago
1b Master equation.ipynb	Renamed and ordered notebooks	2 months ago
1c Quantum control.ipynb	Renamed and ordered notebooks	2 months ago
1d Operators and states.ipynb	Renamed and ordered notebooks	2 months ago
2a Lattices.ipynb	Renamed and ordered notebooks	2 months ago
2b Circuit-QED.ipynb	Renamed and ordered notebooks	2 months ago
2c Spin-boson model.ipynb	Renamed and ordered notebooks	2 months ago
Chebyshev and Lanczos.ipynb	chebyshev expm and the class now admit an estimate of the operator ba	4 months ago

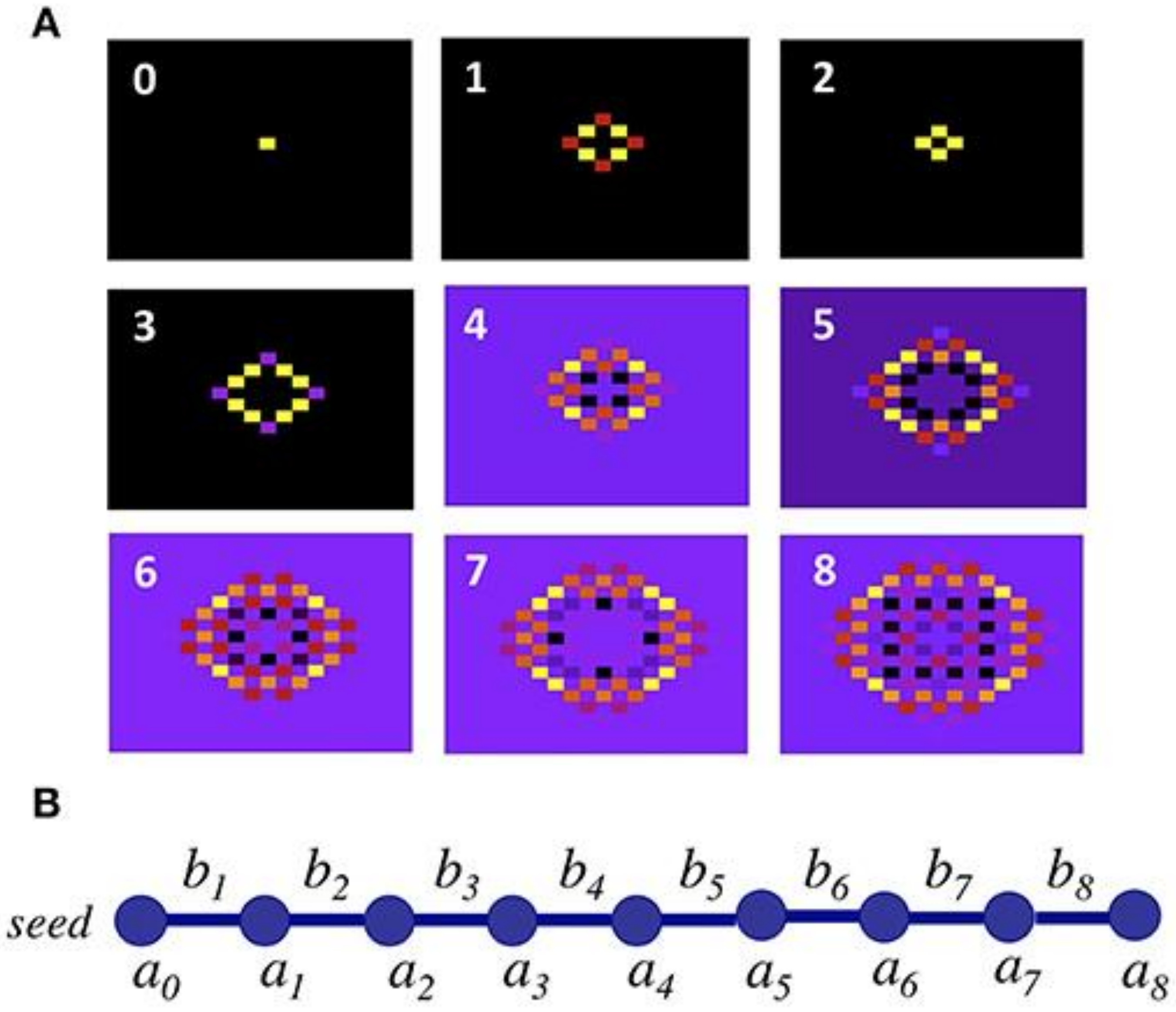
Higher dimensional problems



Lanczos orbitals

Well known tool from Condensed Matter Physics and strongly correlated electrons.

Feiguin, A.E. and Allerdt, A. Frontiers in Physics, 7, p.67 (2019)



Tool #4: Polaron tight-binding model

$$H = \frac{\tilde{\Delta}}{2}\sigma^z O^\dagger_{-f} O_f + \sum_k \omega_k a_k^\dagger a_k + \sigma^x \sum_k \frac{\tilde{\Delta}}{\sqrt{L}}\left(f_k a_k^\dagger + f_k^* a_k\right)$$

$$\Theta = \sum_k \frac{|f_k|^2}{L} \qquad b_0 = \frac{1}{\sqrt{\Theta}} \sum_k \frac{f_k}{\sqrt{L}} a_k$$

Remaining orthogonal modes found by Lanczos recursion

$$H = \frac{\tilde{\Delta}}{2}\sigma^z e^{2\Theta\sigma^x b_0^+} e^{-2\Theta\sigma^x b_0} + \tilde{\Delta}\Theta\sigma^x\left(b_0^+ + b_0\right) + \sum_i t_i \left(b_{i+1}^+ b_i + b_i^+ b_{i+1}\right) + \sum_i \nu_i b_i^+ b_i$$

*See also A. W. Chin et al, Journal of Mathematical Physics **51**, 092109 (2010)*

Tool #2: Polaron tight-binding model

$$H = \frac{\widetilde{\Delta}}{2}\sigma^z O_{-f}^{\dagger} O_f + \sum_k \omega_k a_k^{\dagger} a_k + \sigma^x \sum_k \frac{\widetilde{\Delta}}{\sqrt{L}}\left(f_k a_k^{\dagger} + f_k^* a_k\right)$$

$$\Theta = \sum_k \frac{|f_k|^2}{L} \qquad b_0 = \frac{1}{\sqrt{\Theta}} \sum_k \frac{f_k}{\sqrt{L}} a_k$$

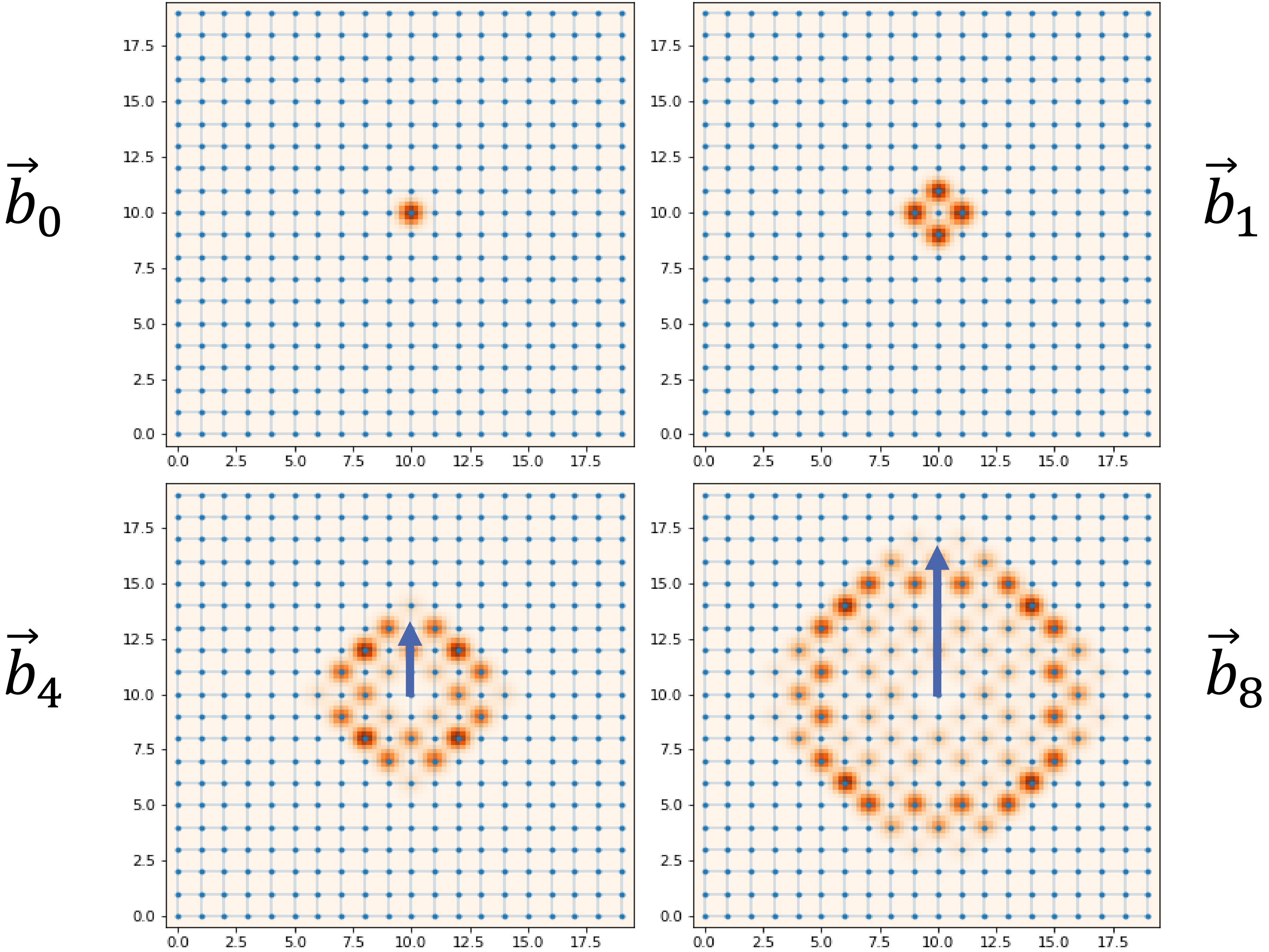
Remaining orthogonal modes found by Lanczos recursion

$$\vec{b}_{n+1} \propto \mathbf{\Omega}\, \vec{b}_n - \sum_{m \le n} \left(\vec{b}_m, \Omega \vec{b}_n\right) \vec{b}_m$$

$$\mathbf{\Omega}_{ij} = \delta_{ij} \omega_i$$

*See also A. W. Chin et al, Journal of Mathematical Physics **51**, 092109 (2010)*

Lanczos orbitals



SeeQ 0.1

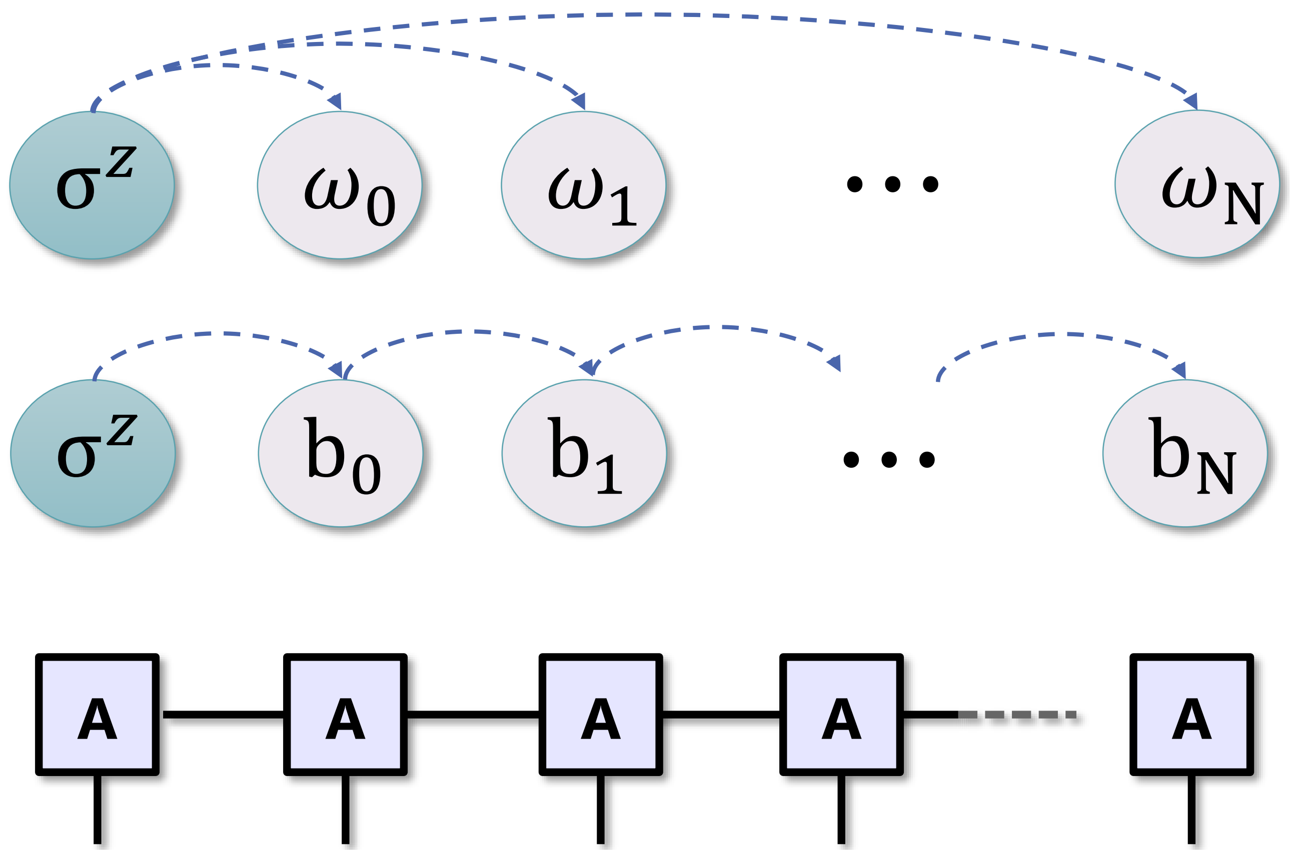
DOI 10.5281/zenodo.3470760

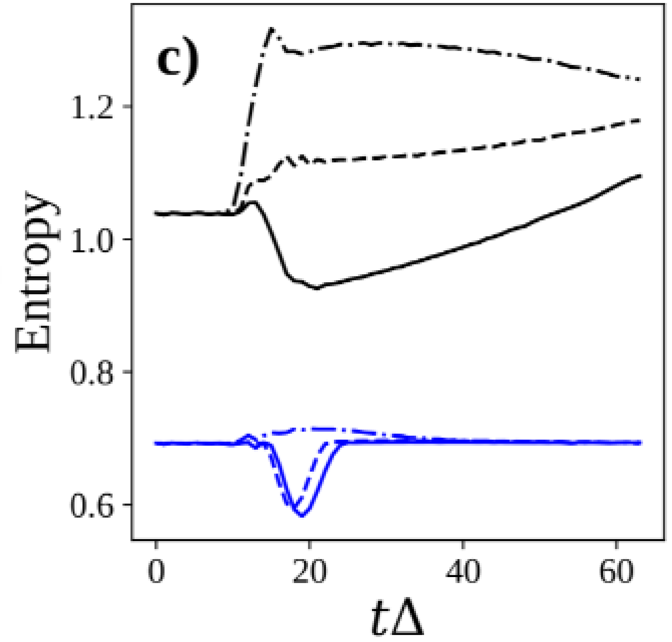
Tool #3: Matrix Product State ansatz

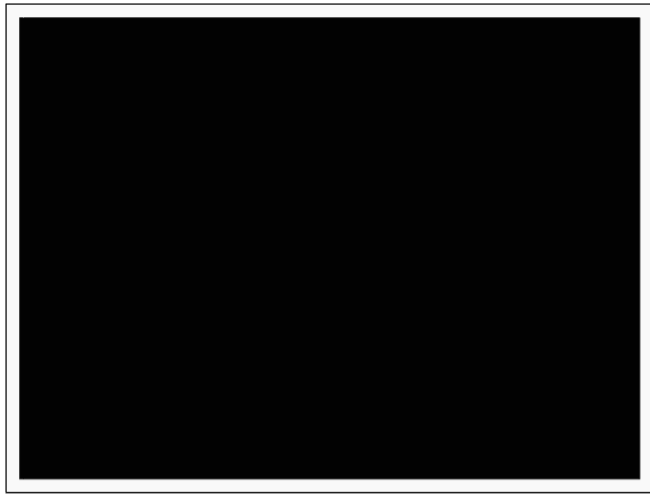
Spin-boson

Chain mapping

Tensor network representation

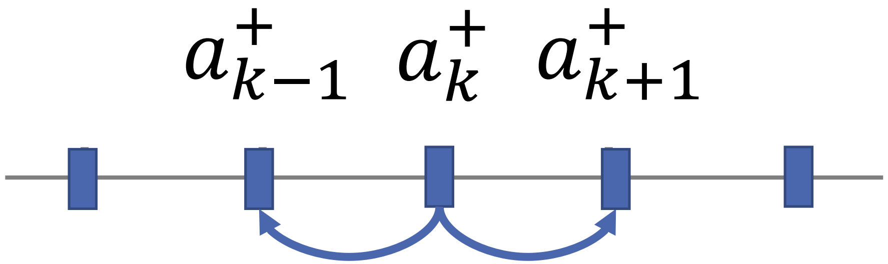




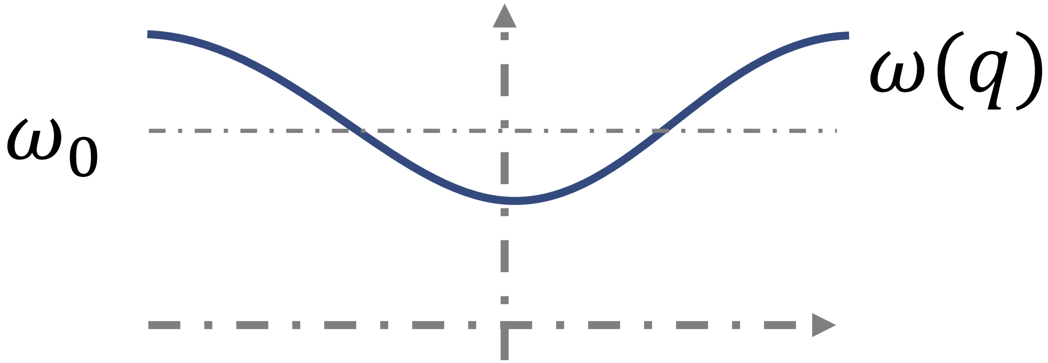


Local Hamiltonian enables simpler, Trotter evolution.
Polaron method allows using small tensors.

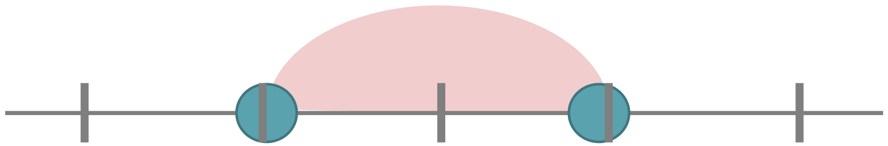
Photonic band



$$H_{ph} = \sum_{k} \omega_0 a_k^{+} a_k + \sum_{\langle kl \rangle} J_{kl} a_k^{+} a_l$$



Subradiant states



$$H = \frac{\Delta}{2}\sigma^z + H_{photon} + \sum_{r,k} \sigma_r^x g_k\left(e^{ikx_r} a_k + e^{-ikx_r} a_k^+\right)$$

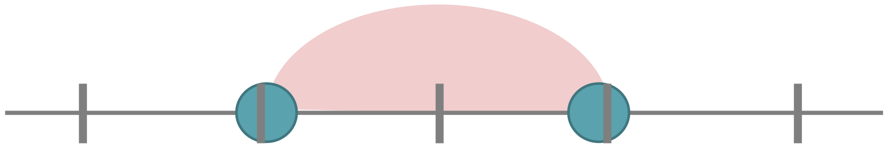
$\Delta \simeq \omega_0$

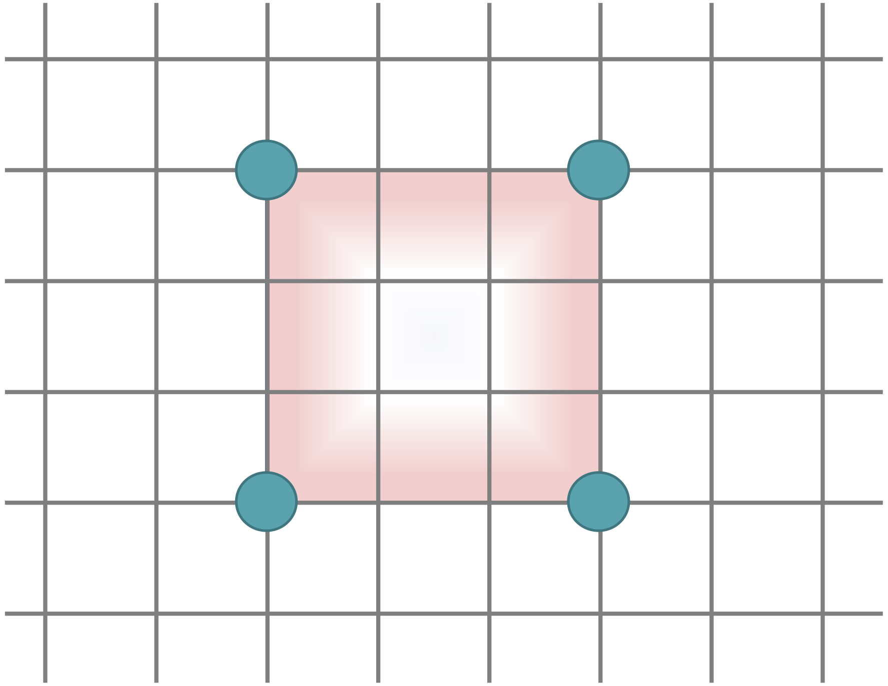
$$H_{int} = \sum_k g_k(\sigma_1^- + \sigma_2^-)a_k^+ + H.c$$

$$(\sigma_1^+ - \sigma_2^+)|0, vac\rangle$$

Lan Zhou *et al*, Phys. Rev. A 78, 063827 (2008)
A. Gonzalez-Tudela *et al* Phys. Rev. Lett. 106 (2011)

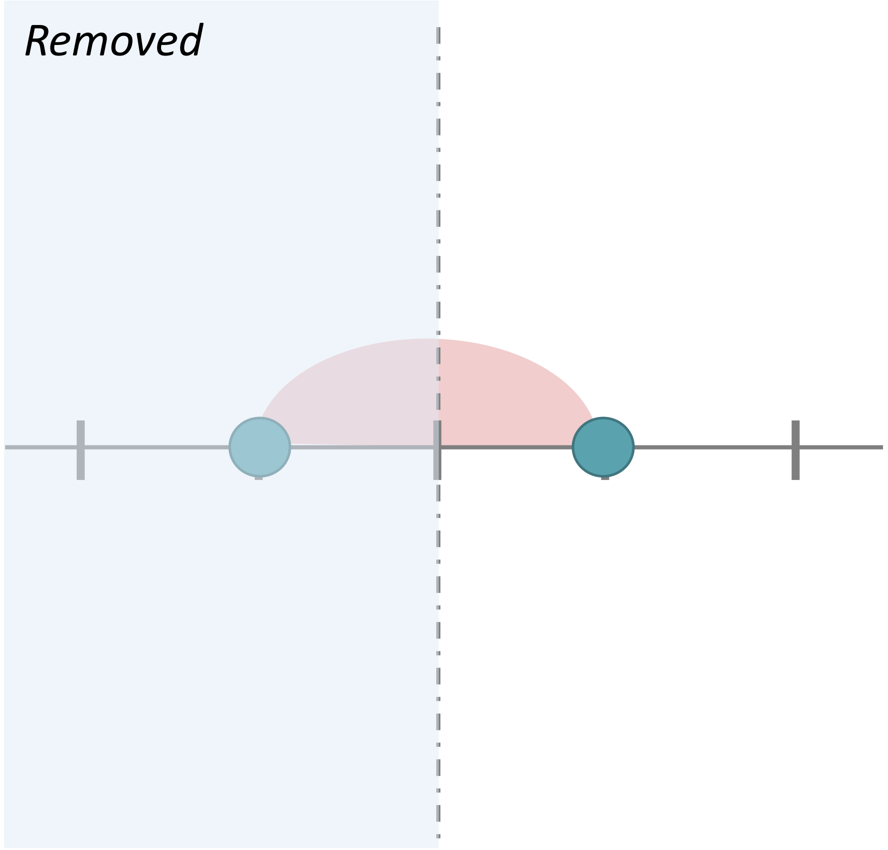
Subradiant states

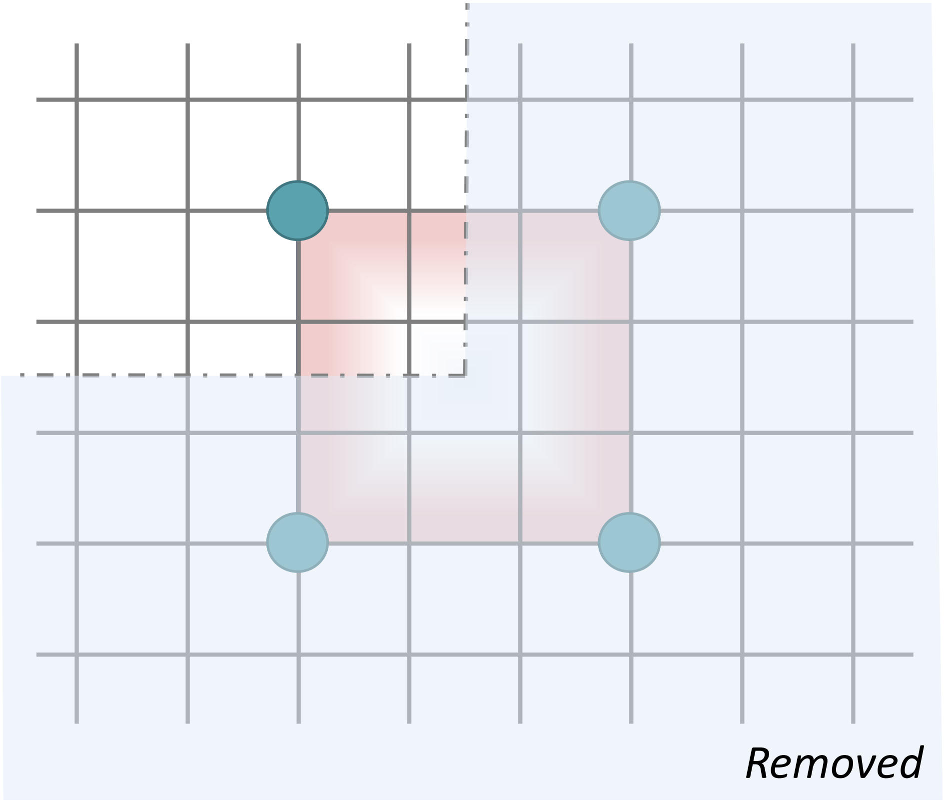




A. González-Tudela and J. I. Cirac, Phys. Rev. A 96, 043811 (2017).

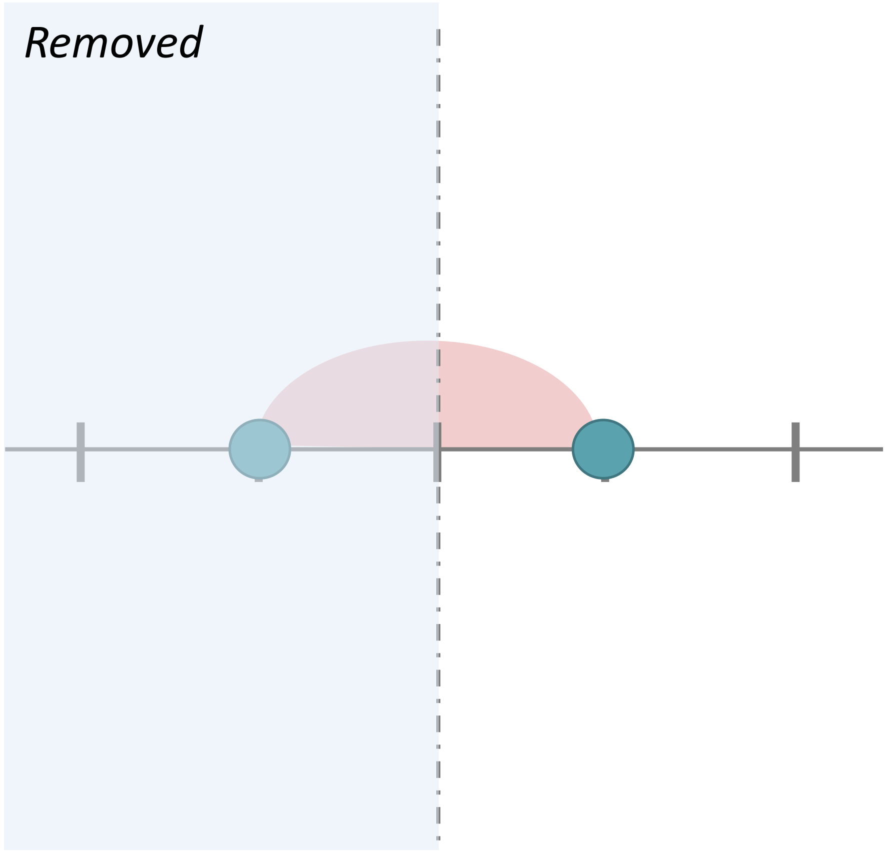
Corner states

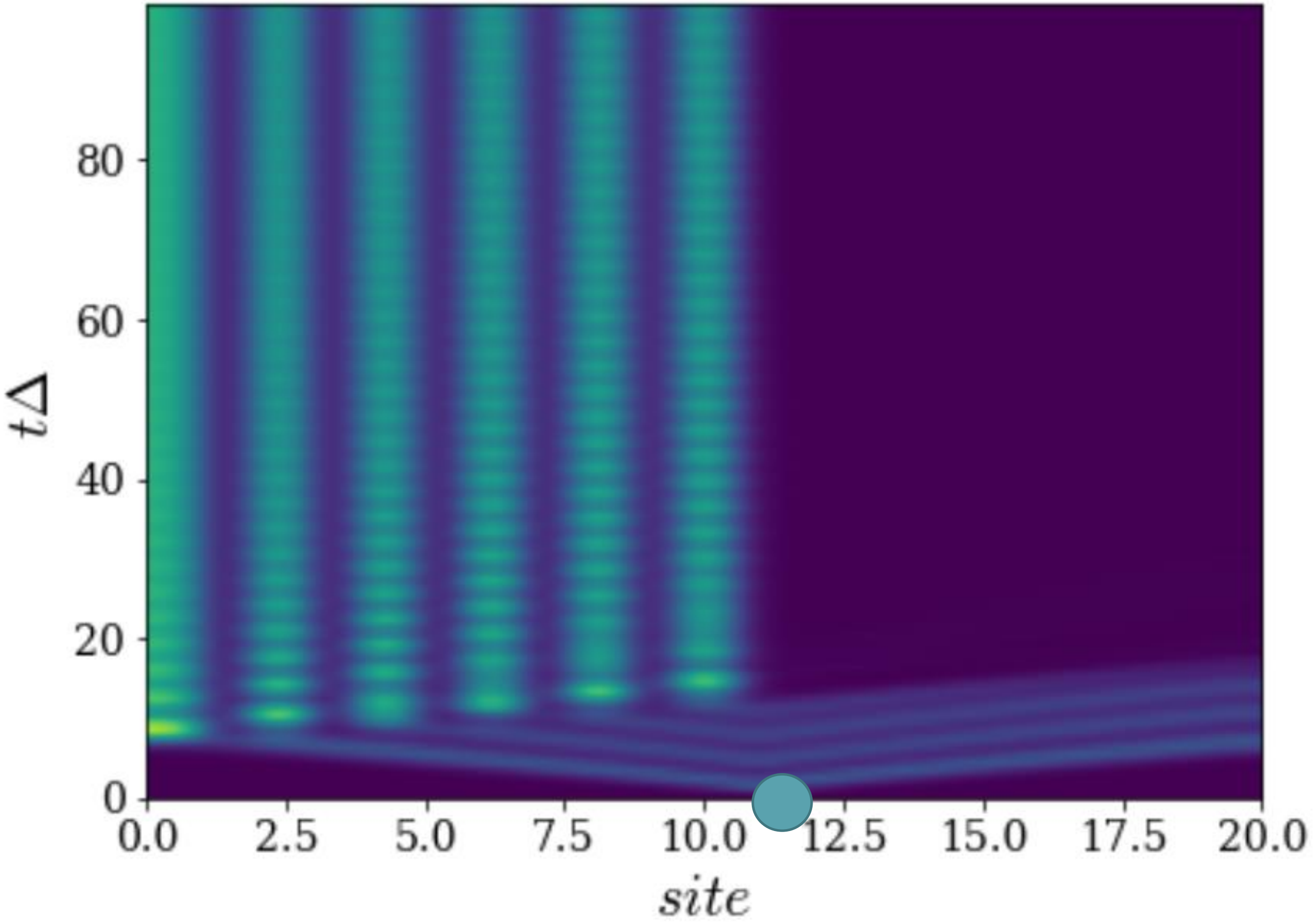




A. Feiguin, JJGR, A. González-Tudela, arXiv:1910.00824

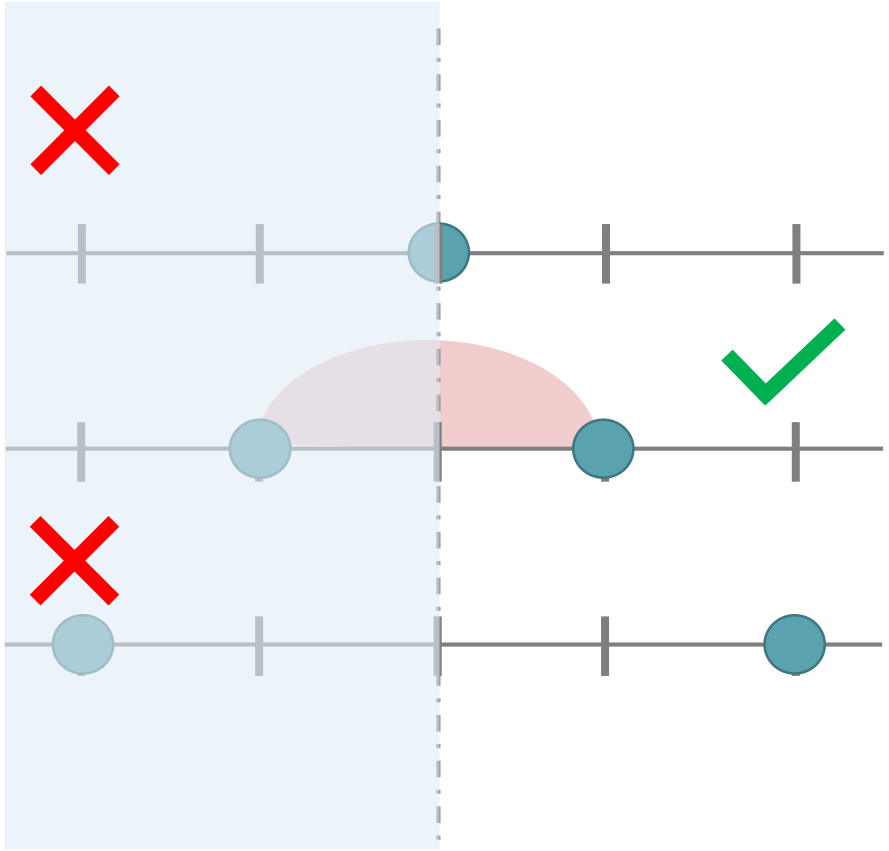
Corner states

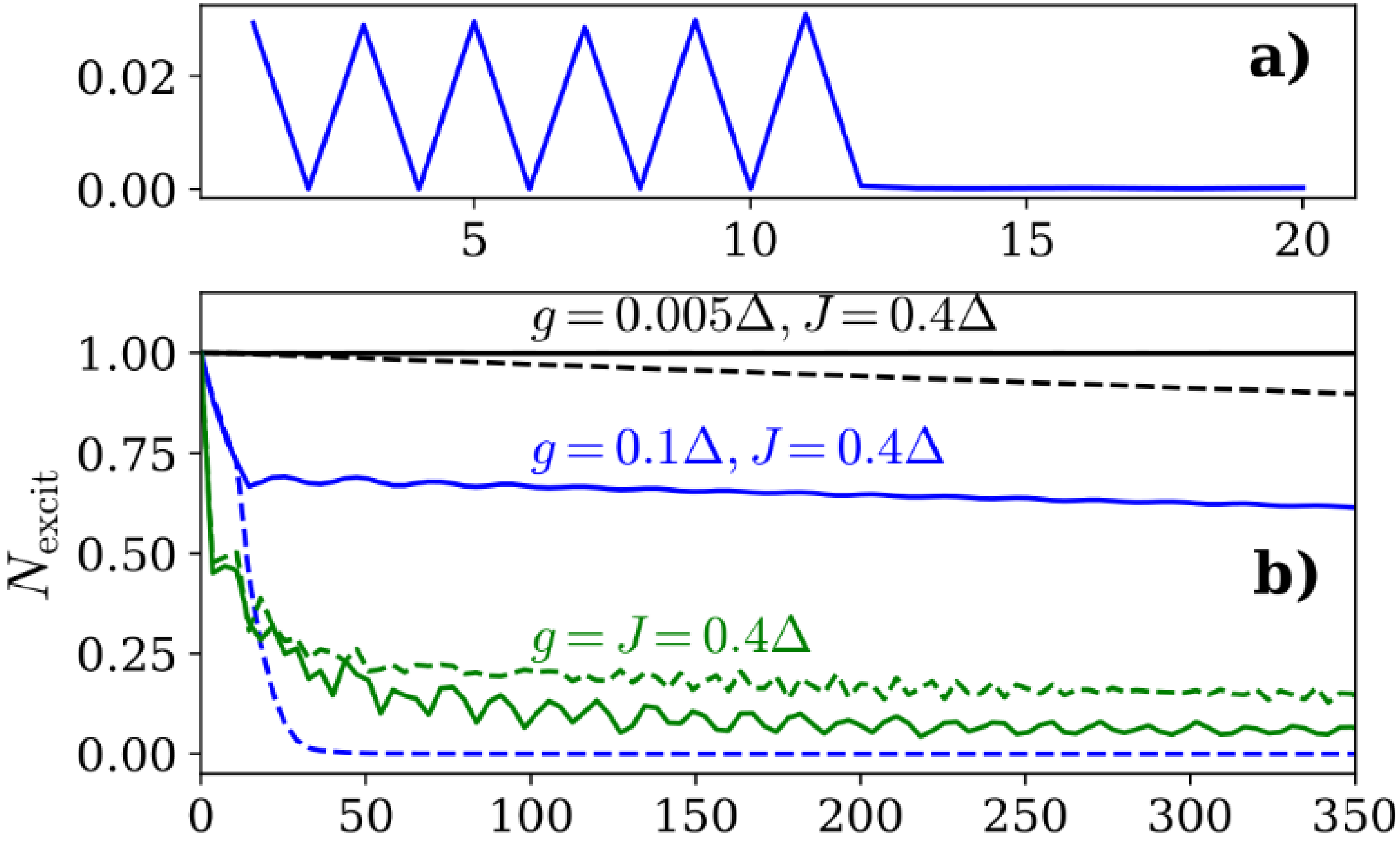




A. Feiguin, JJGR, A. González-Tudela, arXiv:1910.00824

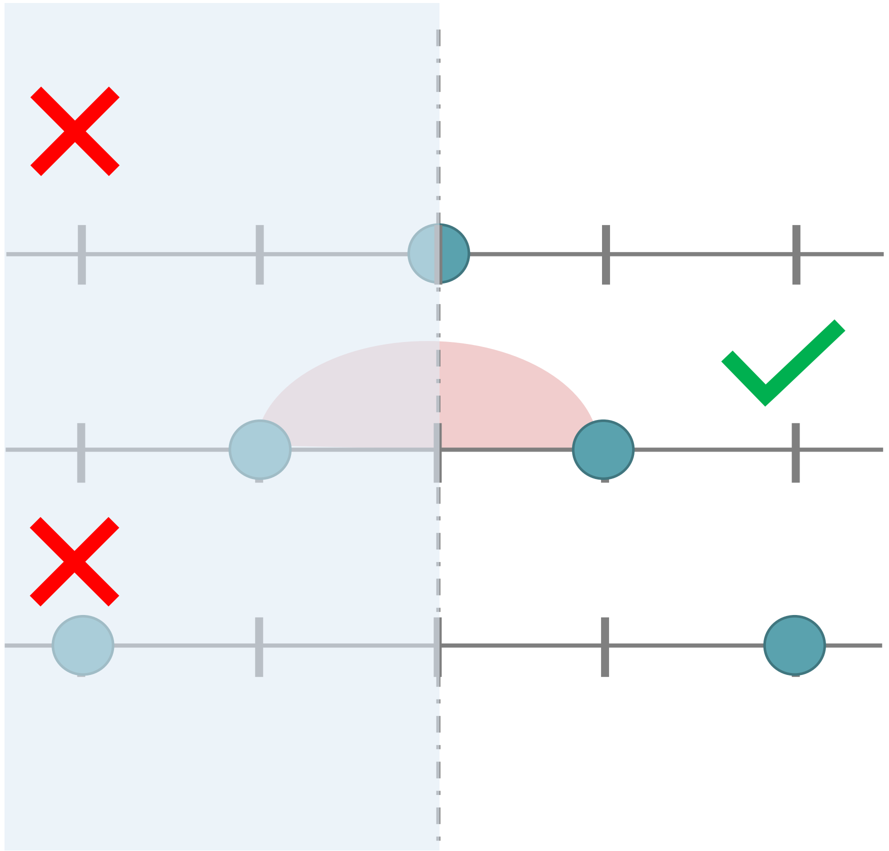
Corner states in 1D

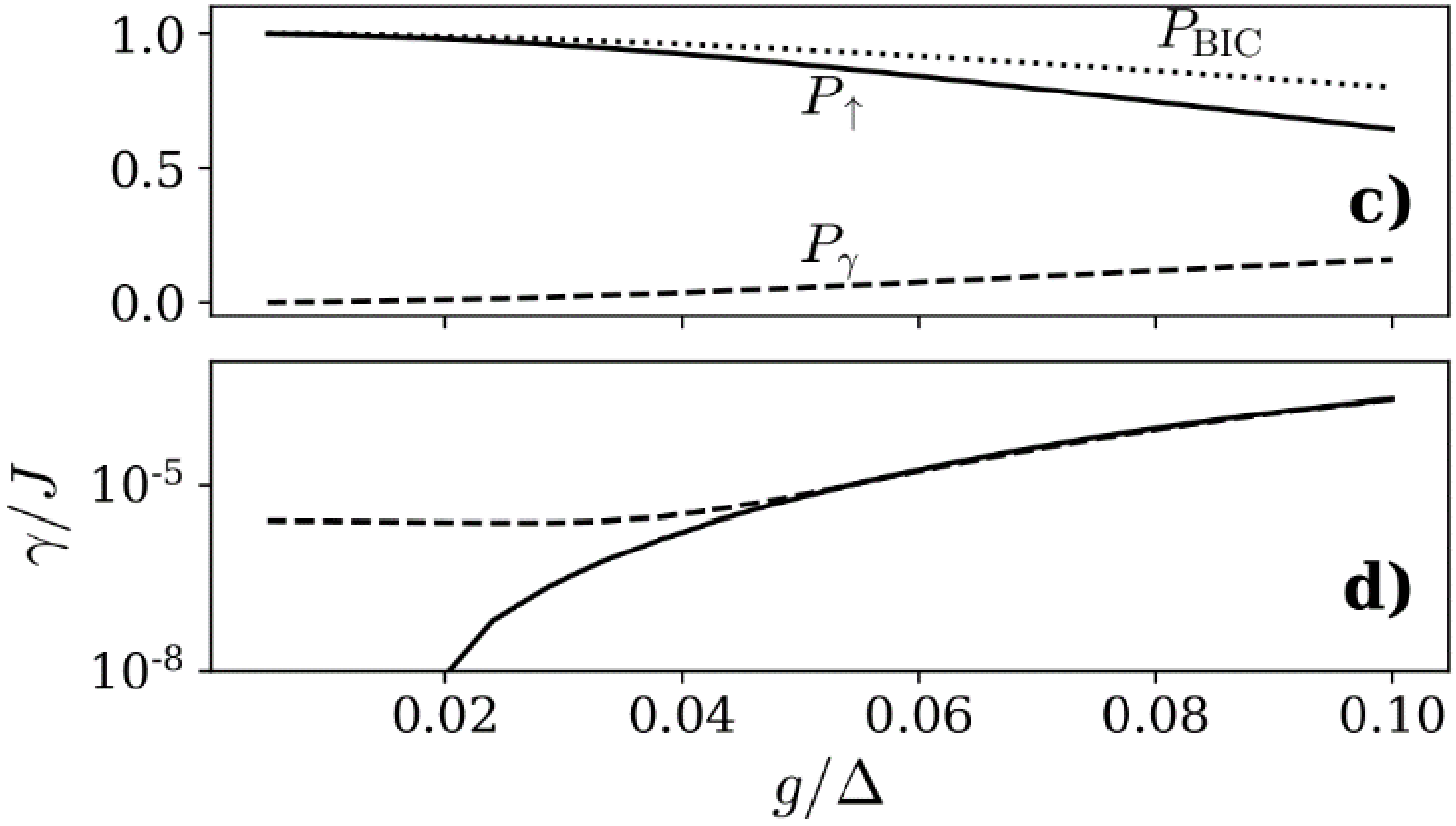




A. Feiguin, JJGR, A. González-Tudela, arXiv:1910.00824

Corner states in 1D



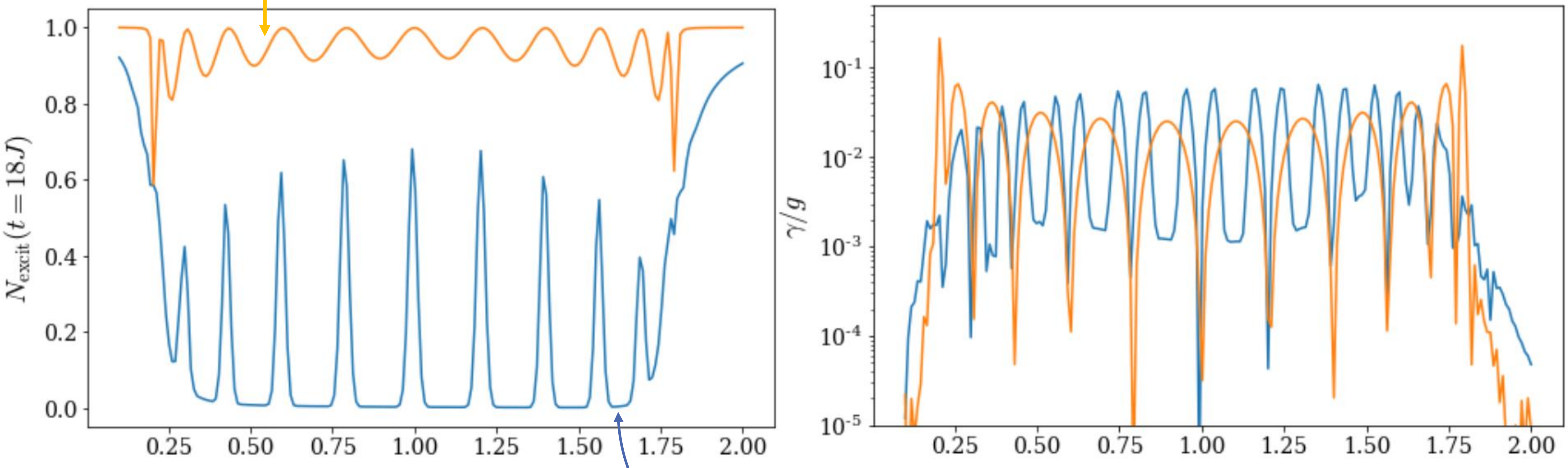


Ultrastrong coupling

A. Feiguin, JJGR, A. González-Tudela, arXiv:1910.00824

Tuning the emitter & coupling

$g = 0.05\Delta$

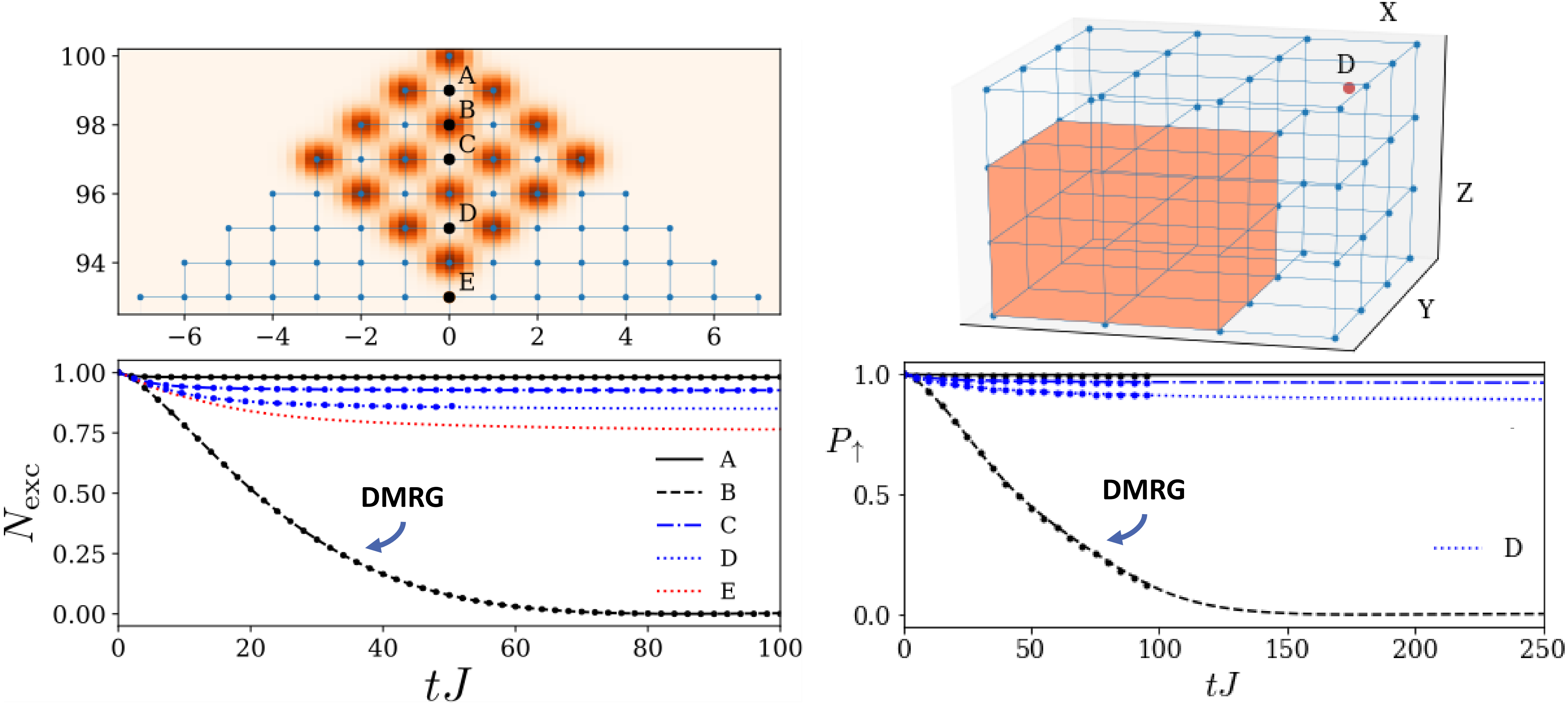


Δ/ω_0 Δ/ω_0

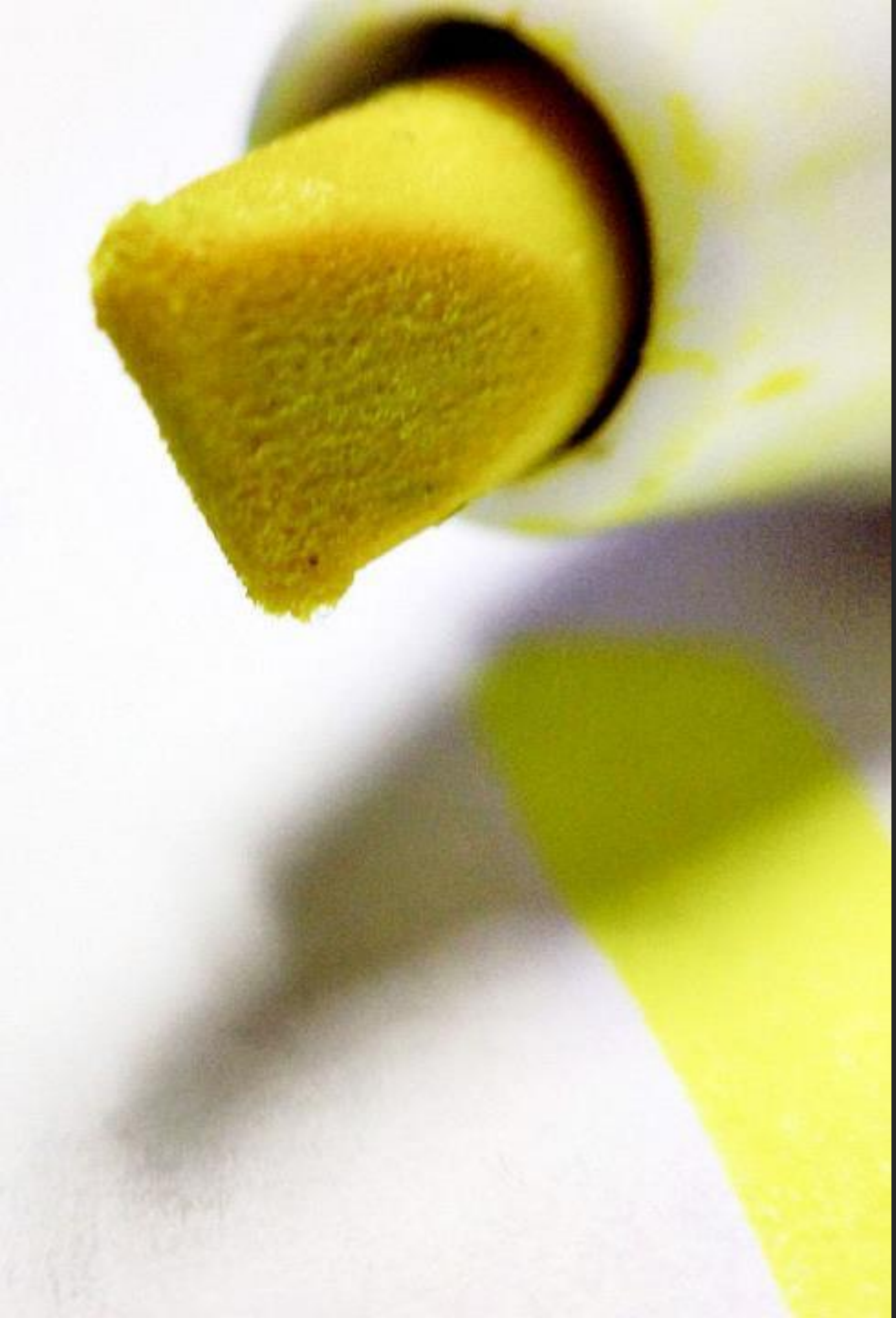
$g = \Delta$

A. Feiguin, JJGR, A. González-Tudela, arXiv:1910.00824

Corner states in 2D and 3D



A. Feiguin, JJGR, A. González-Tudela, arXiv:1910.00824



Main ideas

- Access to **new regimes** of light matter interaction in the lab
- Theoretical tools to analyze **ultrastrong coupling** photonics
- Enabling tool to test many fundamental approximations.
- Interesting prospects for two or more scatterers.

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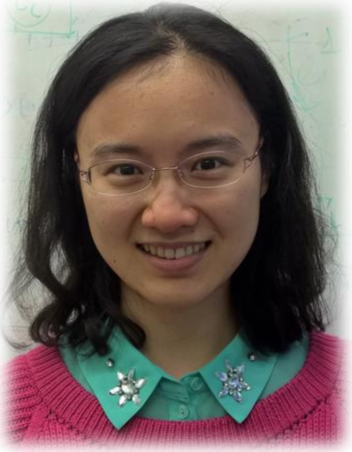

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